Intrinsic states of deformed odd-A nuclei in the mass regions ($151 \leq A \leq 193$) and ($A \geq 221$)

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A review of the empirical data on intrinsic states of odd-A nuclei in the mass range $151 \leq A \leq 193$ and $A \geq 221$ is presented. Global summaries of the data are presented in tables for each isotopic and isotonic chain, wherein the excitation energy, the $\log ft$ values, the moment-of-inertia parameter, and the decoupling parameter (for $K=\frac{1}{2}$ bands) are listed for single-particle, vibrational admixed, and pure vibrational states. Similar data are separately presented for three-quasiparticle excitations in the rare-earth region. Taking guidance from the systematics on nuclear deformation, the single-particle deformed potential for axially symmetric and reflection-symmetric shapes (the Nilsson model) modified by the hexadecapole deformation is used to interpret the data. Other variations of the Nilsson model, which include axially asymmetric shapes (γ deformation) and especially reflection-asymmetric shapes (octupole deformation), have also been used to interpret the data in certain limited regions. Systematics for the intrinsic excitations are presented and discussed in terms of these models. The newly emerging regions of the octupole-quadrupole deformation and superdeformation are also discussed.

CONTENTS

I. INTRODUCTION

The binding of the neutrons and protons of the nucleus involves a complex interplay of all of the nucleons in the nucleus. In view of the complexity of this many-bodied force and the large number of the degrees of freedom which it implies, it is indeed remarkable that it may be approximated by a harmonic-oscillator potential to which a spin-orbit term has been added. This extreme simplification is at least in part possible because the outermost nucleons are quite weakly bound to the rest of the nucleus and can be approximated as "free" nucleons in the potential of the rest of the nucleus.

Thus for a majority of the deformed intrinsic states included in this survey, we assume a harmonic-oscillator potential and an axially symmetric prolate deformed nuclear shape which can be treated using the Nilsson model (Nilsson, 1955; Nilsson *et al.*, 1969). The energy levels of these more normal deformed nuclei are classified by intrinsic state and rotational motion, as in molecules. The low-lying intrinsic states of odd-A nuclei are assigned single-particle quantum numbers identifiable in this harmonic-oscillator-potential model. We make the assumption that one can separate the one- and three-quasiparticle intrinsic motion from the collective vibrations and rotations of the nucleus. This, in turn, implies that energies of intrinsic state, of vibrations, and of rotations are different enough so that intrinsic motion can follow adiabatically the vibrations which, in turn, follow the rotations. Actually, the vibrations and intrinsic states often have very similar energies, and even the rotations do not differ enough to prevent some mixing. A coupling of these basic modes is therefore always present to a greater or lesser extent. Indeed, a rich variety of new phenomena observed in the past two decades is now considered to be the result of the interplay of the intrinsic and the collective aspects of motion, along with the twists and the pushes provided by the Coriolis force and the residual interactions, like the pairing. One of the minor themes of this review is the coupling of the vibrations and the intrinsic states.

While this review takes its cue from the previous reviews of Bunker and Reich (1971) on the rare earths and Chasman *et al.* (1977) on the actinides, it substantially extends these earlier reviews and emphasizes nuclei in the transition regions between spherical and deformed nuclei where new nuclear shapes and their manifestations are observed. An important theme in this review is the evolving evidence for octupole features in the odd-A actinides and, to a lesser extent, in the rare earths. It is also possible to begin to see the energy and Coriolis effects of the collapse of Nilsson orbits into the more degenerate shell-model orbits in these transition regions.

The other major topic of this review is the shell structure as a function of the quadrupole and octupole deformations and its use in calculating potential surfaces for a variety of nuclear shapes. Shell structure relates closely to such diverse subjects as superdeformation and the anomalous values of the decoupling parameters for some $K=1/2$ bands.

The effect of the hexadecapole deformation, ϵ_4, particularly on the intruder states, is briefly reviewed. We also touch on the possibility that the intrinsic states of odd-A deformed nuclei may be described using the group-theoretic treatment of the Interacting Boson-Fermion Model (IBFM) and the Hartree-Fock-Bogoliubov (HFB) self-consistent field calculations.

Of course, the main topic here, as in the previous two reviews, is the systematics of the intrinsic states of odd-A rare-earth and actinide nuclei. Very impressive theoretical developments, which impinge directly on this review, have occurred over the past decades. Among these are the broader recognition and use of deformed shell gaps and associated "magic" numbers, the wedding of liquid-drop and single-particle motion in the Strutinsky shell-correction method, and the cranked shell model. These developments have added new dimensions to our understanding of the level structure and other properties of the deformed nuclei. Experimental developments have been even more impressive because of the advent of the heavy-ion accelerators: new and far superior detector systems coupled with better data analysis techniques. This has culminated in a manifold expansion of nuclear spectroscopy. We can now measure nuclear level energies with far greater precision and in more numbers. The richness now available of the level energy data in a given nucleus is indeed revealing of the advancements made on the experimental side. It has also become possible to study new nuclear species farther from the line of beta stability. Among the new and exciting phenomena discovered in the mass regions of our interest are backbending and multiple bandcrossings in the even-even as well as in the odd-A systems; alignment and decoupled bands; shape coexistence and shape transitions as, for example, in the fission isomers; configuration dependence of pairing correlations; superdeformed shapes; and yrast traps.

Because of this large volume of new experimental and theoretical information, it no longer proved feasible to treat each nucleus with a separate table as was done in the two earlier reviews. Instead, we have used a more "global" approach. Our format for this systematics utilizes columns for Nilsson configurations and rows for nuclei in each isotopic/isotonic sequence. While the nuclear citation data are not quite as obvious as in the previous reviews, the comparison of systematics is especially facilitated. By including both the rare-earth and the actinide odd-A deformed nuclei in the same review, it has proven particularly convenient to show the interesting comparison between the surprisingly similar systematics of the neutron rare-earth orbitals and the corresponding proton actinide orbitals.

Effort has been made to include all the data published before June 1, 1989. We have also included a number of preprints/papers made available after that date that provided important new data or that were especially relevant to the discussion. Only recent references have been included in our bibliography. We do not include the references already covered by Bunker and Reich (1971) and Chasman *et al.* (1977) if a recent and more complete research covering the same nucleus has since become available.

In Sec. II we discuss the interplay between nuclear shapes and shells in the data on intrinsic excitations. In Sec. III we consider some basic features of the single-particle-plus-rotor model and highlight the new developments, such as the octupole-quadrupole deformed single-particle model. Section IV describes briefly the methods used in making configurational assignments. The empirical data on intrinsic excitations in the rare-earth region are discussed in Sec. V, with the detailed systematics presented in Sec. VI. Likewise, the empirical data on intrinsic excitations in the actinide region are presented in Sec. VII, and the systematics is discussed in Sec. VIII. The conclusions from our study are summarized in Sec. IX.

II. SHAPES, SHELLS, AND CORRESPONDING DEFORMATIONS IN NUCLEI

During the last decade we have seen renewed experimental and theoretical emphasis on the existence of a variety of nuclear shapes. These have been the subject of many recent reviews and books (Brack *et al.*, 1972; Kumar, 1972; Mackintosh, 1977; Ragnarsson *et al.*, 1978; Kumar, 1984; and Ragnarsson and Sheline, 1984). It is well known from molecular spectroscopy that the shape determines the nature of the intrinsic states and their degeneracies. Similarly, symmetry breaking in going from spherical to prolate deformed nuclei gives rise to a splitting of the degeneracies of the shell-model states into the less degenerate Nilsson states. In analogy, the further symmetry breaking of Nilsson states in going to quadrupole-octupole shapes, as we shall see, gives rise to the doubling of bands in odd-A nuclei. In this section we treat the general problem of the effect of shells on nuclear shapes and what particular shells or magic numbers arise from a given shape as a function of deformation. Then, in Sec. III, we consider the intrinsic states arising from the quadrupole-hexadecapole deformations and those arising from the quadrupole-octupole deformations.

A. Nuclear shapes from nuclear shell structure

Qualitatively, shell structure implies the existence of an inhomogeneity in the single-particle energy levels which divides them into groups (a kind of approximate degeneracy) interspersed by energy gaps where there are no, or fewer, levels. These gaps define regions of enhanced stability in which shell effects occur, whereas regions in which there are large numbers of levels lead to instability and antishell effects. Bohr and Mottelson (1975) generalized the analysis of shell structure for spherical systems. The condition for shell structure is

$$\frac{\partial e}{\partial n}:\frac{\partial e}{\partial l}=a:b \ , \tag{2.1}$$

where $a:b$ is an integer ratio corresponding classically to the ratio of the number of radial and angular oscillations in a closed orbit. Here n and l are the radial and angular oscillator quantum numbers and e is the energy eigenvalue.

Figure 1, which is based on the Bohr and Mottelson (1975) treatment (see Ragnarsson *et al.*, 1978), represents the way the shell structure of a system influences shapes. Contour lines in the energy in Fig. 1 are drawn for different values of a and b corresponding to different radial potentials. For light and medium-heavy nuclei, much of the shell structure can be approximated by that of a spherical harmonic oscillator in which $(\partial e/\partial n):(\partial e/\partial l)=2:1$ (solid contour lines). This 2:1 scheme, which implies that the s and d, and p and f, orbitals are close together in energy, favors quadrupole (P_2) deformations.

For restricted regions of the heavy nuclei beyond

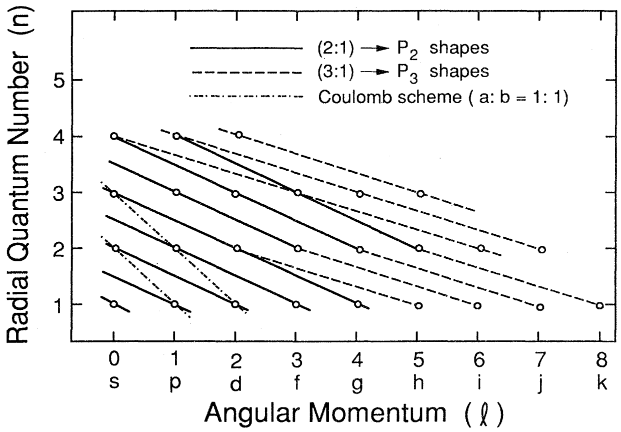

FIG. 1. Contour lines of constant energy in an n,l plane, where n is the radial quantum number and l the angular momentum quantum number. Shell structure is obtained for $(\partial e/\partial n):(\partial e/\partial l)=a:b$, where a and b are small integers. For $a:b=2:1$, the solid lines correspond to a pure harmonic oscillator and favor quadrupole (P_2) shapes. Dashed lines approximate the infinite square well for $a:b=3:1$, with $\bar{l}$ and $\bar{s}$ parallel, and correspond to P_3 (octupole) shapes. Dot-dashed lines correspond to the Coulomb potential with $a:b=1:1$. From Ragnarsson *et al.* (1978).

^{208}Pb, and to a lesser extent for nuclei in the neutron-excess light rare earths, the shell effects (dashed line in Fig. 1) follow more closely the scheme $(\partial e/\partial n):(\partial e/\partial l)=3:1$, with l and s parallel as shown by the dashed contour lines in Fig. 1. This scheme is approximately reproduced by the infinite square well, the Woods-Saxon, or the folded Yukawa potentials. Indeed, the appropriate orbitals in the nuclei just beyond ^{208}Pb are observed to be very close together and near the Fermi surface. For example, the $1j_{15/2}$ and $2g_{9/2}$ neutron orbitals are 1.42 MeV apart in ^{209}Pb, while the $1i_{13/2}$ and $2f_{7/2}$ proton orbitals are 1.70 MeV apart in ^{209}Bi. The corresponding orbitals in the rare earths are the $1i_{13/2}$ and $2f_{7/2}$ neutron orbitals and the $1h_{11/2}$ and $2d_{5/2}$ proton orbitals. Since the $Y_{3\mu}$ matrix elements are large between these sets of proton orbitals on the one hand and similar sets of neutron orbitals on the other, octupole shapes are strongly favored. Indeed, the octupole mode is expected to be competitive with the quadrupole mode in a rather restricted region of the actinides and, to a lesser extent, in the rare earths. The dot-dashed contours in Fig. 1 correspond to $(\partial e/\partial n):(\partial e/\partial l)=1:1$, which is the expected shell structure for the Coulomb potential, for example, in hydrogenlike atoms. Possible stable hexadecapole deformation would involve $(\partial e/\partial n):(\partial e/\partial l)=4:1$ and is not shown as contour lines in Fig. 1. Since we do not observe the appropriate states close together and near the Fermi surface for this 4:1 scheme anywhere in the nuclear periodic table, we cannot expect to find stable hexadecapole deformation in the low-energy region of nuclei. However, as we shall see later in this review, relatively small amounts of dynamic hexadecapole deformation do significantly influence the intrinsic single-particle levels.

Because of the existence of both quadrupole and octupole nuclear shapes, we expect two different kinds of Nilsson level diagrams—one involving quadrupole deformation with small amounts of dynamic hexadecapole deformation and a second involving a combination of quadrupole and octupole deformation. These diagrams are developed in Sec. III.

B. The systematics of shell effects

Bohr and Mottelson (1975) also presented the generalized condition of shell structure for separable nonspherical systems as

TABLE I. "Magic numbers" for nuclei having various quadrupole deformations and shapes. The numbers correspond to calculations for the harmonic oscillator without $l\cdot s$, or l^2 terms. When these terms are employed, the numbers in parentheses result. The last column gives the "magic numbers" for an asymmetric rotor.

ϵ_2	-1.2	-0.75	0	0.6	0.86	1.0	0.87 ($\gamma=30°$)
$\omega_\perp:\omega_z$	1:3	1:2	1:1	2:1	3:1	4:1	3:2:1
			2				
	6	6	8	4	4	4	4
	12	14	20	10	6	6	8
			(28)				
	22	26	40(50)	16	12	8	14
	36	44	70(82)	28	18	14	22
		68	112(114,126)	40(40–46)	24	20	
		100	168(184)	60(60–68)	36	26	
		140		80(80–90)	48	32	
				110(110–118)	60	44	
				140(140–150)	80	56	
				182	100		

$$\frac{\partial e}{\partial n_a}:\frac{\partial e}{\partial n_b}:\frac{\partial e}{\partial n_c}=a:b:c \ , \tag{2.2}$$

where a, b, and c are integers and n_a, n_b, and n_c are the three quantum numbers characterizing the eigenstates, such as the Cartesian quantum numbers (n_x, n_y, n_z) in the harmonic-oscillator case. For the simple harmonic oscillator, the condition on $a:b:c$ can be transformed into a condition on the oscillator frequencies $\omega_x:\omega_y:\omega_z$. For axially symmetric deformations, $\omega_x=\omega_y=\omega_\perp$, a plot of the simple harmonic-oscillator eigenvalues gives rise to very strong shell effects and large gaps for $\omega_\perp:\omega_z=1:1$, 2:1, 1:2, 3:1, 1:3, etc. The number of nucleons up to the gap corresponds to closed shells and has been popularized by the term "magic numbers." In the harmonic-oscillator scheme, these magic numbers of the 1:1 (spherical) scheme are 2, 8, 20, 40, 70, 112, and 168. For the 2:1 scheme, they are 2, 4, 10, 16, 28, 40, 60, 80, 110, 140, and 182. For the 1:2 scheme, the numbers are 2, 6, 14, 26, 44, 68, 100, 140, 190, etc. All of these "closed-shell" magic numbers are listed in Table I (Sheline, 1976).

As is well known, spin-orbit coupling affects the number of nucleons that can occupy shells in spherical nuclei. While the spin-orbit coupling does not completely destroy the shell structure, it reduces it significantly and, for the higher mass numbers, shifts the magic numbers to higher values, e.g., from 40 to 50, 70 to 82, 112 to 126, etc. In a similar way, spin-orbit coupling affects the magic numbers for deformed nuclei. In Fig. 2 (Ragnarsson *et al.*, 1978), a plot of shell energy versus nucleon number is shown for a number of different shell structure schemes. This energy is the additional binding energy of the nucleus associated with shell effects, as calculated in the Strutinsky formalism discussed in the following section. The results for the simple harmonic oscillator without spin-orbit coupling are shown as dashed curves, whereas those with spin-orbit coupling are shown as solid curves. The four figures labeled a, b, c, and d are cuts through the shell-energy landscape for, respectively, spherical nuclei with the quadrupole deformation parameter (defined in Sec. III.A) $\epsilon_2=0$ and $\omega_\perp:\omega_z=1:1$; prolate nuclei with $\epsilon_2=0.60$ and $\omega_\perp:\omega_z=2:1$; oblate nuclei with $\epsilon_2=-0.75$ and with $\omega_\perp:\omega_z=1:2$; and triaxial nuclei with $\epsilon_2=0.866$ and $\gamma=30°$ and $\omega_x:\omega_y:\omega_z=3:2:1$. The solid curves in Fig. 2 make quite clear the decreased shell effects and the changes in the magic numbers or shell closures that result from spin-orbit coupling. Further, Fig. 2 not only indicates a sequence of magic numbers for increasing prolate deformations, but also for oblate deformations and for triaxial deformations.

C. The systematics of deformations from the Nilsson-Strutinsky formalism

In Strutinsky's (1967, 1968) formulation, these shell effects are added to a liquid drop to make a total potential-energy surface that may, in some cases, have slightly different shell closures than the shell structure itself. The effect of adding both the liquid drop and the spin-orbit coupling tends to spread out the magic numbers or shell closures, particularly when they involve deformed nuclei. The complete sequence of magic numbers, both for the simple harmonic oscillator and when spin-orbit coupling and the liquid-drop contributions are included, is shown in Table I (Sheline, 1976). We are now able to use Fig. 2, Table I, and other information in an attempt to explain the systematics of nuclear deforma-

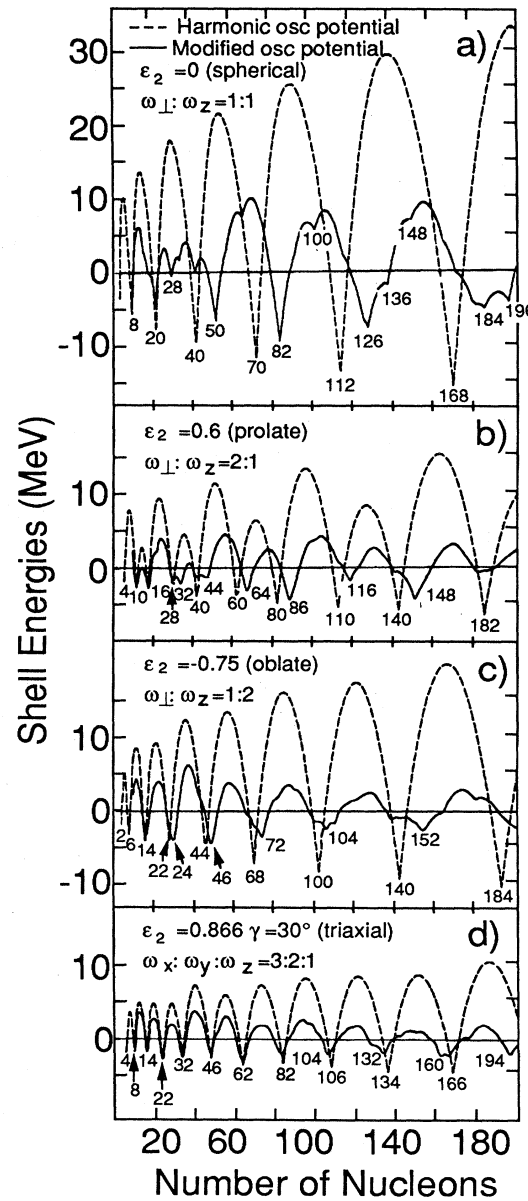

FIG. 2. A slice through the contour diagrams of shell correction energies for deformation $\epsilon_2=0$, 0.6 (prolate superdeformation), -0.75 (oblate superdeformation), and $\epsilon_2=0.866$, $\gamma=30°$ (axially asymmetric shape). The pure harmonic oscillator is shown dashed; the modified harmonic oscillator, with a solid line. From Ragnarsson *et al.* (1978).

tions and some of the diversity of nuclear shapes.

A knowledge of the interplay between the potential energy of the liquid drop and that for shell effects as a function of the deformation is necessary to understand the systematics of quadrupole deformations. Figure 3 (Sheline, 1976) shows this interplay and gives six schematic possibilities, two each for low-A nuclei, medium-A nuclei, and high-A nuclei. For each type of nucleus, we show a shell effect involving very few levels at $\epsilon_2=0$ and a shell effect at $\epsilon_2=0.6$. Level density is also shown schematically. The liquid drop is shown as a dashed parabolic curve, while the final potential energy is shown as a solid curve.

The normal deformations in the rare earths and actinides ($\epsilon_2=0.2-0.3$ in the rare earths and $0.1-0.25$ in the actinides) are not caused by the shell effects themselves but by a cooperation involving an antishell effect for spherical shapes and the Coulomb effect of the liquid drop at the larger deformations. This is seen by the locations of the minima on the solid curves in the center right and lower right parts of Fig. 3.

This interplay between the liquid drop and shell effects is known as the microscopic-macroscopic method of Nilsson and Strutinsky. It has been used by a large number of authors to study the systematics of nuclear quadrupole deformations (see, for example, Ragnarsson and Sheline, 1984). These calculations have been performed for nuclei along the line of beta stability as well as for the neutron-excess and the neutron-deficient nuclei, and the results have been shown to correlate very closely with experiment. Consequently, the systematics of deformations for the normal range of deformation ($\epsilon_2=0.2-0.3$) is very well understood. These developments allow us to predict the intrinsic configurations in the confidence that we know the appropriate quadrupole deformations.

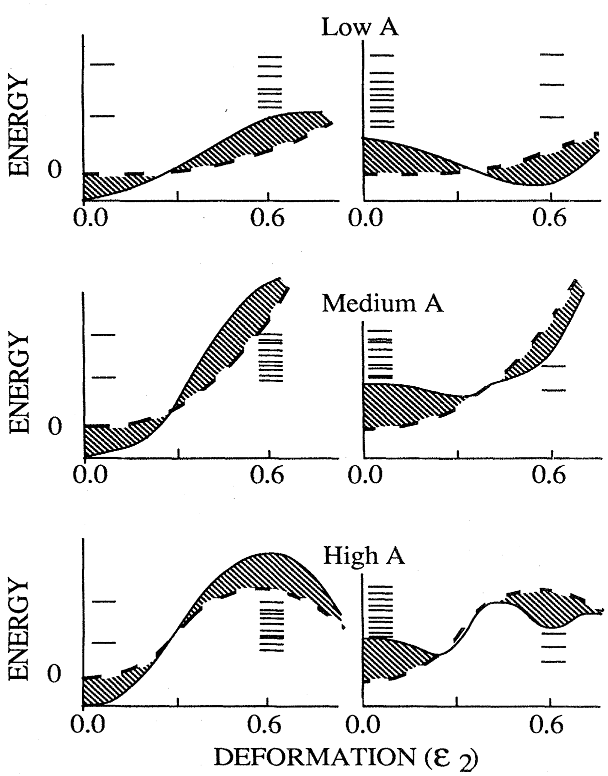

FIG. 3. Liquid-drop potential energy (dashed line) vs deformation for light, medium, and heavy nuclei. Superimposed on it are the shell effects (crosshatched lines) for the situation corresponding to low single-particle-level density at $\epsilon_2=0$ and high single-particle-level density at $\epsilon_2=0.6$ (shown at left), and for the reverse situation (shown at right). The total potential energy is shown by a solid line. The role of the antishell effect in producing a minimum at $\epsilon_2\approx0.3$ for medium A and high A may be clearly seen. From Sheline (1976).

D. Super quadrupole deformation and the intrinsic excitations

In the heaviest nuclei, the approximate cancellation of the surface tension and the Coulomb effects produces a flat potential-energy surface at deformation $\epsilon_2\approx0.6$. The shell effects, seen in Fig. 2 at $\epsilon_2=0.6$, operate to make a very clear second minimum in the actinides. The observation of this second minimum by Polikanov (1968) in terms of the fission isomers was the first identification of superdeformation. On the other hand, in the rare earths, the steepness of the liquid-drop potential makes the shell effect less prominent (see Fig. 3). Indeed, we only see the superdeformation at relatively high spin, where the larger moment of inertia for the superdeformed band makes it possible for the high-spin states to compete successfully.

Starting with Table I and Fig. 2, we can estimate where best to look for superdeformed bands in nuclei. In the actinides, this clearly corresponds to the region from 141 to 151 neutrons centered around neutron number 148, which achieves the maximum shell effect. This theoretical expectation is confirmed experimentally, as shown in Fig. 4 where the log of the half-lives of the odd-A Pu and Am fission isomers is plotted against neutron number. The most stable fission isomers clearly have neutron numbers in the vicinity of 147–148.

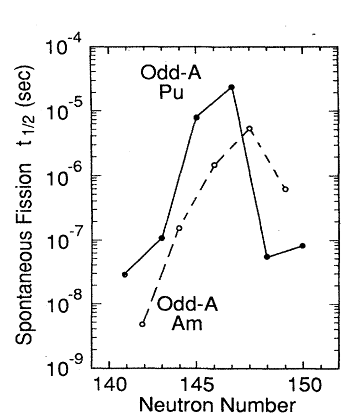

FIG. 4. Log of the spontaneous fission half-lives for odd-A Pu and odd-A Am isotopes vs neutron number. Largest half-lives occur around $N=147$.

In a similar way, for proton numbers 60–68 and for neutron numbers 80–90, we expect to see strong shell effects centered at the middle of these regions leading to superdeformation with $\epsilon_2 \simeq 0.6$ and axes ratio 2:1. It is quite clear, therefore, why we see superdeformed bands in ^{148}Gd (Deleplanque *et al.*, 1988), ^{150}Gd (Fallon *et al.*, 1989), and ^{152}Dy (Twin *et al.*, 1986). These nuclei have 64, 64, and 66 protons and 84, 86, and 86 neutrons, respectively, and are therefore doubly magic. The magic character of these neutron and proton numbers also explains the experimental observation of superdeformed bands in the odd-A nuclei $^{149}_{64}$Gd$_{85}$ (Haas *et al.*, 1988), $^{151}_{66}$Dy$_{85}$ (Rathke *et al.*, 1988), and $^{191}_{80}$Hg$_{111}$ (Moore *et al.*, 1989) falling within the region of interest in this review. However, the possible observation of superdeformation in the light Sr, Ba, Ce, Nd, and Os nuclei must await experimental confirmation and theoretical treatment, although it is clear that in most cases magic neutron and/or proton structures are involved.

Using the existing Nilsson model, it is possible to make some educated guesses on the intrinsic configurations associated with the odd-A superdeformed nuclei. The "ground state" in the superdeformed second minimum has been determined to be $5/2^+$ for ^{239}Pu. However, the Nilsson model does not predict any intrinsic $5/2^+$ state close to the ^{239}Pu Fermi surface for $\epsilon_2=0.6$. Hamamoto and Ogle (1975) suggested that the spin-orbit coupling be increased by $\approx 20\%$ compared to the standard parameters. With this prescription the Nilsson configuration corresponding to the $5/2^+$ in ^{239}Pu is $5/2^+[633]$. Recent suggestions for the intrinsic-state bandheads in the odd-A superdeformed rare earths are $\pi(i_{13/2})^2\nu(j_{15/2})^1$ and $\pi(i_{13/2})^4\nu(j_{15/2})^1$ for the nuclei $^{1149}_{64}$Gd$_{85}$ and $^{151}_{66}$Dy$_{85}$, respectively. In view of the very tentative nature of these assignments for the intrinsic states in the odd-A superdeformed nuclei, we have chosen not to include them in our tables of assignment (Secs. V and VII). However, it is clear that as the experimental and theoretical treatment of superdeformation becomes more secure, these assignments will become one of the more important challenges in future reviews.

III. THE PARTICLE-ROTOR MODEL AND RECENT DEVELOPMENTS

The data presented in this review are normally discussed and interpreted in terms of the particle-rotor model (Bohr and Mottelson, 1975). The model is widely used to interpret the low-lying spectra of odd-A nuclei and has been extensively discussed in earlier reviews (Bunker and Reich, 1971; Ogle *et al.*, 1971; Stephens, 1975; Chasman *et al.*, 1977; Engeland, 1984). Therefore only a summary of the well-known basic ideas and the important results is presented. More emphasis is given to the new developments in the model, which add to our understanding of the single-particle-level data.

The particle-rotor model includes a single-particle Hamiltonian $H_{\rm sp}$, such as the Nilsson (1955), describing the particle motion in an average deformed nuclear potential. An approximate but effective description of odd-A nuclei follows by treating the odd nucleon moving in one of the single-particle orbitals and coupling its motion to the rotation of an inert core, which comprises the rest of the nucleons. The second term of the model is, therefore, a rotational Hamiltonian $H_{\rm rot}$. The total Hamiltonian may thus be written as

$$H = H_{\rm sp} + H_{\rm rot} + H_{\rm res} , \qquad (3.1)$$

where $H_{\rm res}$ denotes the contribution arising from the residual interactions such as pairing. The interaction of the odd nucleon with the quadrupole and octupole surface vibrations of the even-even core is taken into account by the proper coupling terms. These coupling terms, which correspond to the quasiparticle-phonon interactions, are neglected here; their effect will be considered at the appropriate places.

A. Single-particle Hamiltonian

Many versions of the single-particle Hamiltonian for deformed nuclei are now available. These differ either in the form of the potential or in the shape parametrization. Some of these versions include the original harmonic-oscillator potential of Nilsson (1955); the treatment of Gustafson *et al.* (1967) using the modified harmonic oscillator (MHO); and similar versions with some further modifications presented by Lamm (1969), Nilsson *et al.* (1969), and Bengtsson (1975). Details of these variations may now be found in many standard textbooks (Davidson, 1968; Irvine, 1972; Preston and Bhaduri, 1975; Soloviev, 1976; Pal, 1982). An excellent treatment is given by Bohr and Mottelson (1969, 1975). The deformation parameters ϵ_2, ϵ_4 are used to characterize the MHO potential. Transformation of (ϵ_2,ϵ_4) to the alternative deformation parameters $(\beta_2,\beta_4,\beta_6)$ may be found in Bengtsson *et al.* (1989).

A more realistic Woods-Saxon potential (Woods and Saxon, 1954; Brack *et al.*, 1972) has also been widely used to perform extensive calculations, and a detailed reference to various authors may be found in Chasman *et al.* (1977). A systematic comparison of the MHO (Nilsson potential) and the Woods-Saxon potential calculations has recently been done by Bengtsson *et al.* (1989). Another single-particle potential used is the folded Yukawa potential (Nix, 1971; Bolsterli *et al.*, 1972; Möller *et al.*, 1974). For a spherical shape, the folded Yukawa potential is very close to a Woods-Saxon potential, but the folded Yukawa potential is found to be more useful for generating potential shapes of interest in fission. Both the Woods-Saxon and the folded Yukawa potentials are more realistic than the MHO. However, the single-particle energy levels and eigenfunctions as obtained from various treatments are adjusted to the same set of experimental data and therefore display the same general features. We have therefore chosen to discuss the data mostly in terms of the MHO potential, in view of the historical perspective and its more frequent usage. It has, however, been shown by Leander *et al.* (1982) that the coupling to octupole deformation is stronger in a potential with a realistic flat-bottomed radial shape. Therefore Woods-Saxon and folded Yukawa single-particle potentials are employed to discuss the data on octupole deformed nuclei.

The MHO Hamiltonian for a spheroidal deformation may be written as (Nilsson *et al.*, 1969)

$$H_{\mathrm{sp}}=\frac{p^2}{2m}+\frac{m}{2}[\omega_\perp^2(x^2+y^2)+\omega_z^2z^2] , \tag{3.2}$$

where the quadrupole deformation parameter ϵ_2 (hereafter denoted simply as ϵ without the subscript) is introduced by defining the oscillator frequencies as

$$\omega_z=\omega_0\left[1-\frac{2}{3}\epsilon\right] ,$$
$$\omega_\perp=\omega_0\left[1+\frac{1}{3}\epsilon\right] , \tag{3.3}$$
$$\hbar\omega_0\approx 41A^{-1/3}\ \mathrm{MeV} .$$

It leads to a quadrupole part of the potential (in terms of the spherical harmonics Y_{lm}) proportional to

$$\epsilon\left[1-\frac{1}{6}\epsilon\right]r^2Y_{20}(\theta) \tag{3.4}$$

up to second order in ϵ. The coupling terms of r^2Y_{20} between shells N and $N\pm2$ are eliminated by a transformation to a new set of coordinates (x',y',z') defined as

$$x'=\sqrt{m\omega_\perp/\hbar}\,x ,$$
$$y'=\sqrt{m\omega_\perp/\hbar}\,y , \tag{3.5}$$
$$z'=\sqrt{m\omega_\perp/\hbar}\,z ,$$

and

$$r'^2=x'^2+y'^2+z'^2 . \tag{3.6}$$

The quadrupole deformed potential to first order in ϵ is given by

$$V=\frac{\hbar\omega_0}{2}\left[r'^2-\frac{2}{3}\epsilon r'^2\left[\frac{4\pi}{5}\right]^{1/2}Y_{20}(\theta')\right] , \tag{3.7}$$

where θ' is the angle in the new coordinates.

Higher multipole deformations may be introduced at this stage by adding terms proportional to

$$\epsilon_4r'^2P_4(\cos\theta'),\quad \epsilon_6r'^2P_6(\cos\theta'),\quad \text{and}\quad \epsilon_3r'^2P_3(\cos\theta') , \tag{3.8}$$

where the Legendre polynomials P_4, P_6, P_3, and therefore the parameters ϵ_4, ϵ_6, and ϵ_3 represent the hexadecapole, hexinda-tesserapole, and octupole deformations, respectively. While the octupole shape breaks the reflection symmetry, all the deformation modes introduced so far maintain the axial symmetry. Axially asymmetric shapes can be considered by introducing the γ-deformation parameter (Preston and Bhaduri, 1975). The general single-particle Hamiltonian, which also includes the spin-orbit interaction, may now be written as

$$H_{\mathrm{sp}}=-\tfrac{1}{2}\hbar\omega_0\Delta+\tfrac{1}{2}\hbar\omega_0r'^2\left[1-\tfrac{2}{3}\epsilon\left[\frac{4\pi}{5}\right]^{1/2}\left[Y_{20}\cos\gamma-(Y_{22}+Y_{2\text{-}2})\frac{\sin\gamma}{\sqrt{2}}\right]+2\epsilon_3P_3+2\epsilon_4P_4+2\epsilon_6P_6\right]$$
$$-\kappa\hbar\omega_0'[2\bar{l}_t\bar{s}+\mu(l_t^2-\langle l_t^2\rangle_N)] , \tag{3.9}$$

where κ and μ are adjustable parameters. The operator l_t is the orbital angular momentum constructed in the new coordinates and the corresponding canonically conjugate momentum operators. We shall first consider the axially symmetric deformations so that the term in the square brackets is Y_{20} and

$$H=\tfrac{1}{2}\hbar\omega_0(\epsilon,\epsilon_4,\dots)\left[-\Delta'+\frac{2}{3}\epsilon\frac{1}{2}\left[2\frac{\partial^2}{\partial x'^2}-\frac{\partial^2}{\partial y'^2}-\frac{\partial^2}{\partial z'^2}\right]+r'^2-\frac{2}{3}\epsilon r'^2P_2+2\epsilon_3r'^2P_3+2\epsilon_4r'^2P_4+2\epsilon_6r'^2P_6\right]$$
$$-\kappa\hbar\omega_0'[2\bar{l}_t\bar{s}+\mu(l_t^2-\langle l_t^2\rangle_N)] . \tag{3.10}$$

Approximate constancy of nuclear matter density is imposed by requiring that nuclear volume remain constant with deformation. This in turn requires that the volume enclosed by all equipotential surfaces be simultaneously conserved. For the spheroidal harmonic-oscillator potential, this condition corresponds to

$$\omega_0'^3=\omega_\perp^2\omega_z=\text{constant} . \tag{3.11}$$

In the more general case considered above, the volume conservation simply requires a scaling of ω_0 as

$$\frac{\omega_0^3}{\omega_0'^3}=\frac{1}{(1+\frac{1}{3}\epsilon)(1-\frac{2}{3}\epsilon)^{1/2}}\times\int_{-1}^{+1}\frac{\frac{1}{2}d(\cos\theta')}{(1-\frac{2}{3}\epsilon P_2+2\epsilon_3P_3+2\epsilon_4P_4+2\epsilon_6P_6)^{3/2}} . \tag{3.12}$$

The oscillator frequency ω_0' is obtained from the condition that the nuclear radius be reproduced; a commonly used value is $\hbar\omega_0'=41A^{-1/3}$ MeV.

1. Reflection-symmetric shapes

First we shall discuss the Nilsson diagrams for reflection-symmetric deformations. The cylindrical oscillator basis functions designated by $\Omega^\pi[Nl\Lambda]$ are used for diagonalization of the Hamiltonian. In the limit of large deformations, the so-called asymptotic quantum numbers $\Omega^\pi[Nn_z\Lambda]$ assume special significance, as they can now be used to label the single-particle orbitals and also to classify the connecting transitions. Here, n_z is the number of oscillator quanta along the symmetry axis and $N=n_\perp+n_z$, where $n_\perp=n_x+n_y$ is the sum of oscillator quanta along the x and y axes. The quantum number Λ is the projection of the single-particle orbital angular momentum on the symmetry axis. However, the only conserved quantum number is $\Omega=\Lambda+\Sigma$, which represents the projection of the particle (total) angular momentum j on the symmetry axis. The quantum number Σ ($=\pm\frac{1}{2}$), commonly denoted ↑ or ↓ for up spin or down spin, represents the spin of the single particle. Each single-particle state is therefore twofold degenerate (time-reversed orbits $\pm\Omega$). Parity is denoted by π, which is $+/-$ for even/odd N.

Plots of proton and neutron eigenvalues as a function of the deformation and extensive tabulation of eigenfunctions for the rare-earth and the actinide mass regions may be found in many papers and books. In particular, we refer to Gustafson *et al.* (1967), Nilsson *et al.* (1969), Bohr and Mottelson (1975), Soloviev (1976), Chi (1966), Davidson (1968), and Irvine (1972). Nilsson *et al.* (1969) have presented detailed diagrams showing the effect of ϵ_4 deformation on the single-particle energies. In Figs. 5 and 6, we show the variation of proton and neutron eigenvalues with ϵ_2 and positive values of ϵ_4 for the rare-

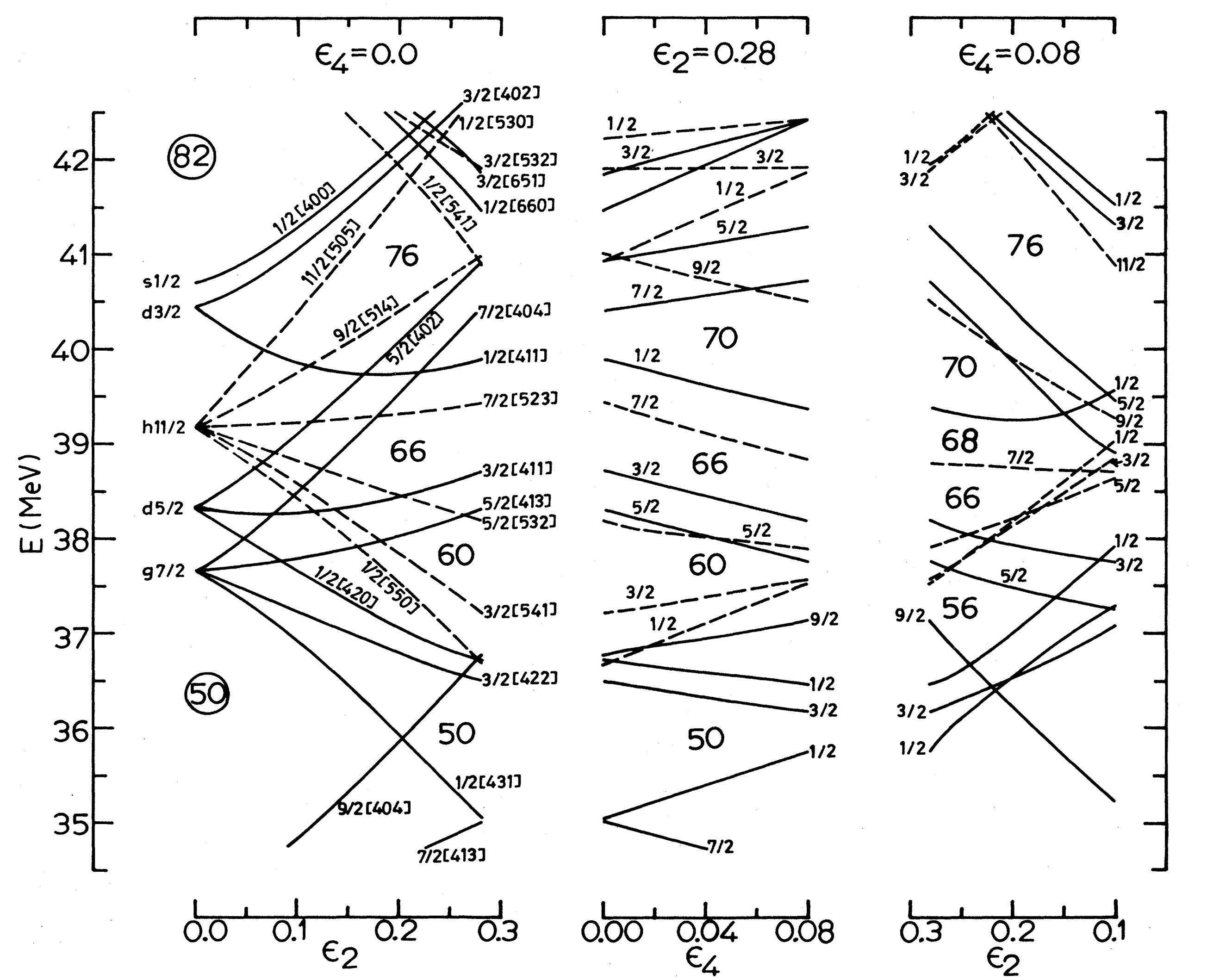

FIG. 5. Single-proton levels in the rare-earth region by using the modified harmonic-oscillator (MHO) potential for $\epsilon_2=0$ to 0.28 with $\epsilon_4=0$, for $\epsilon_4=0$ to 0.08 with $\epsilon_2=0.28$, and for $\epsilon_2=0.28$ to 0.10 with $\epsilon_4=0.08$. The parameters used are $\kappa=0.0620$ and $\mu=0.614$.

earth region. It is clear from these diagrams that the hexadecapole deformation mostly leaves the gaps appearing in the single-particle-level energies, due to quadrupole deformation, unchanged. Exceptions are for the $Z=76$ and $N=118$ gaps, which disappear when ϵ_4 is introduced. It is apparent from these diagrams that $\Omega=\frac{1}{2}$ levels mostly favor small or negative hexadecapole deformations. The most striking feature is the grouping of the levels of the $h_{11/2}$ protons, $i_{13/2}$ neutrons, $i_{11/2}$ neutrons, and, to some extent, the $h_{9/2}$ neutrons (Bengtsson, 1980).

Similar diagrams for the actinide region are presented in Figs. 7 and 8. Here we show only negative ϵ_4 values, because most of the nuclei in this mass region have a negative hexadecapole shape. Similar plots of single-particle levels obtained by using the Woods-Saxon potential may be found for rare earths in Faessler and Sheline (1966) and for actinides in Chasman *et al.* (1977).

As shown in Fig. 9 (Nilsson *et al.*, 1969), the theoretical ground-state deformations in the rare-earth and actinide regions span a large range of (ϵ_2,ϵ_4) values. The single-particle-level structure therefore exhibits considerable changes along a path in the (ϵ_2,ϵ_4) deformation plane taken by nuclei in the rare-earth and actinide regions, as discussed in Secs. VI and VIII.

2. Axially asymmetric shapes

Details of the calculations with the inclusion of axial asymmetry in the single-particle Hamiltonian (Newton, 1960) may be found in Larsson *et al.* (1972) and Larsson (1973). The ϵ_4 deformation was not included in these calculations (Larsson, 1973). It should be pointed out that for $0<\gamma<60°$ Ω is no longer a good quantum number, since there is no axial symmetry. Moreover, Ω refers to the projection on the x axis for oblate shapes. Larsson (1973) shows the behavior of single-particle levels for pro-

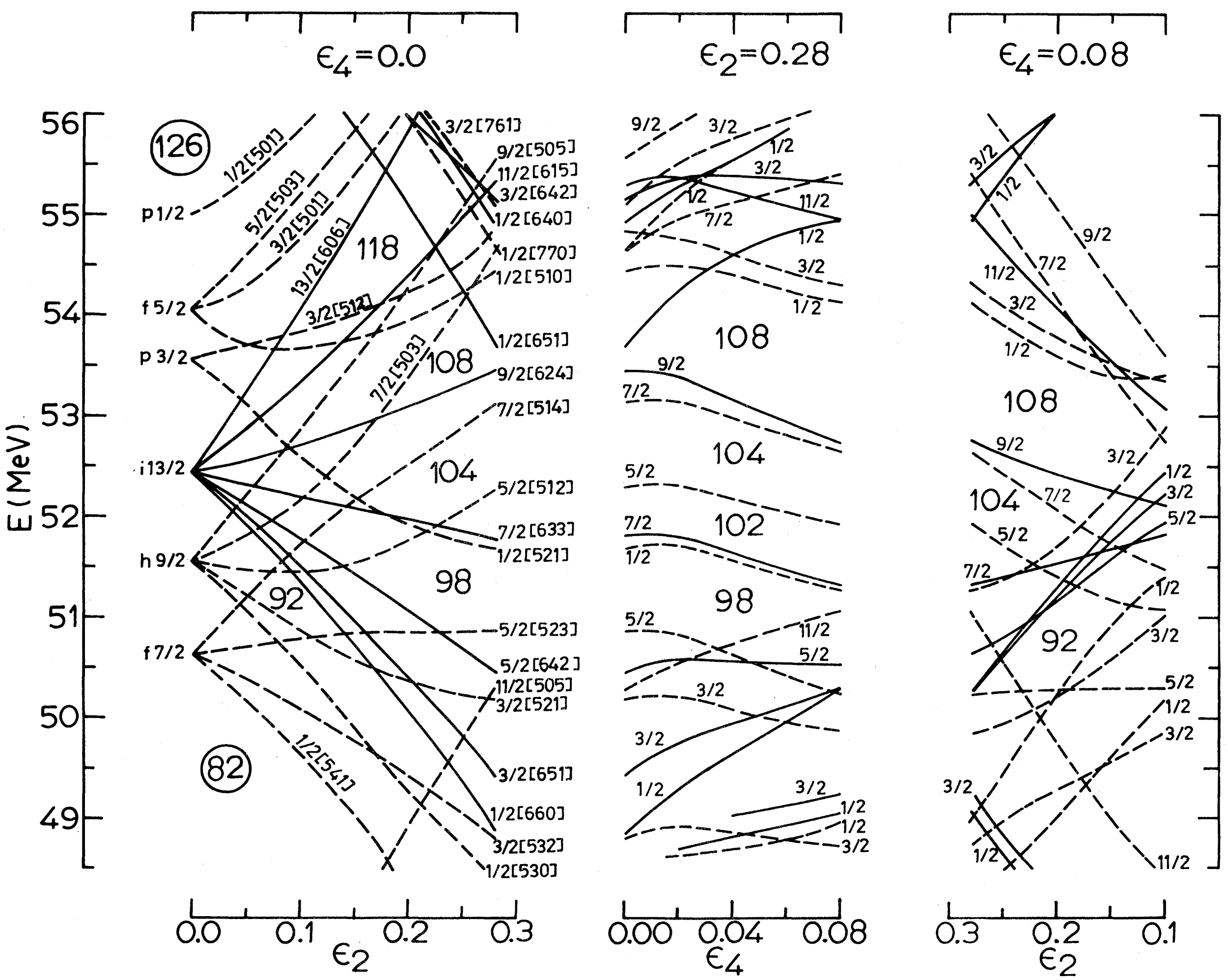

FIG. 6. Single-neutron levels in the rare-earth region by using the modified harmonic-oscillator (MHO) potential for $\epsilon_2=0$ to 0.28 with $\epsilon_4=0$, for $\epsilon_4=0$ to 0.08 with $\epsilon_2=0.28$, and for $\epsilon_2=0.28$ to 0.10 with $\epsilon_4=0.08$. The parameters used are $\kappa=0.0636$ and $\mu=0.393$.

tons and neutrons, respectively, as a function of γ at $\epsilon_2=0.20$. Significant structural changes occur as we go from the prolate to the oblate shape by crossing the γ-deformation valley. Rearrangement of the levels is seen to give rise to new gaps at $N=110$, 116, and 126 for $\gamma\approx30°$. Potential-energy surface calculations using these single-particle levels in the Strutinsky method reveal that prolate equilibrium deformations occur for tungsten nuclei with $A<186$, while for $A=188$ and 190, a minimum of about $\gamma=30°$ is obtained. However, for $A>192$, oblate shapes occur. Similar results are obtained for Os and Pt where the intermediate γ values of $\gamma\simeq20°$ and $\gamma\simeq40°$ occur for $A=190$ and 192, respectively.

3. Reflection-asymmetric shapes

The motivation for the study of reflection asymmetry or octupole deformation in nuclei comes from the fact that any nuclear structure model incorporating the universally dominant quadrupole mode will be tested in quite a new way by octupole deformation because it involves additional symmetry breaking.

It is well known from molecular spectroscopy that one effect of reflection asymmetry is approximately degenerate states of opposite parity. These states have become known as parity doublets (PD's), since they can be described as the symmetry-breaking projections of a single intrinsic state of mixed parity. The experimental spectroscopy expected for odd-A octupole deformed nuclei includes (1) near-lying states of the same spin and opposite parity (PD's); (2) similar magnetic moments for the PD's; (3) enhanced E1 transition between the PD's; (4) low hindrance factors in α decay to both PD bands from the α-decaying parent with the same configuration (this is applicable only in the actinides where appreciable α decay is observed); and (5) decoupling parameters for the PD $K=1/2^{\pm}$ bands of opposite sign, but approaching the same absolute values.

In addition, there is strong evidence (Sheline, 1987) for

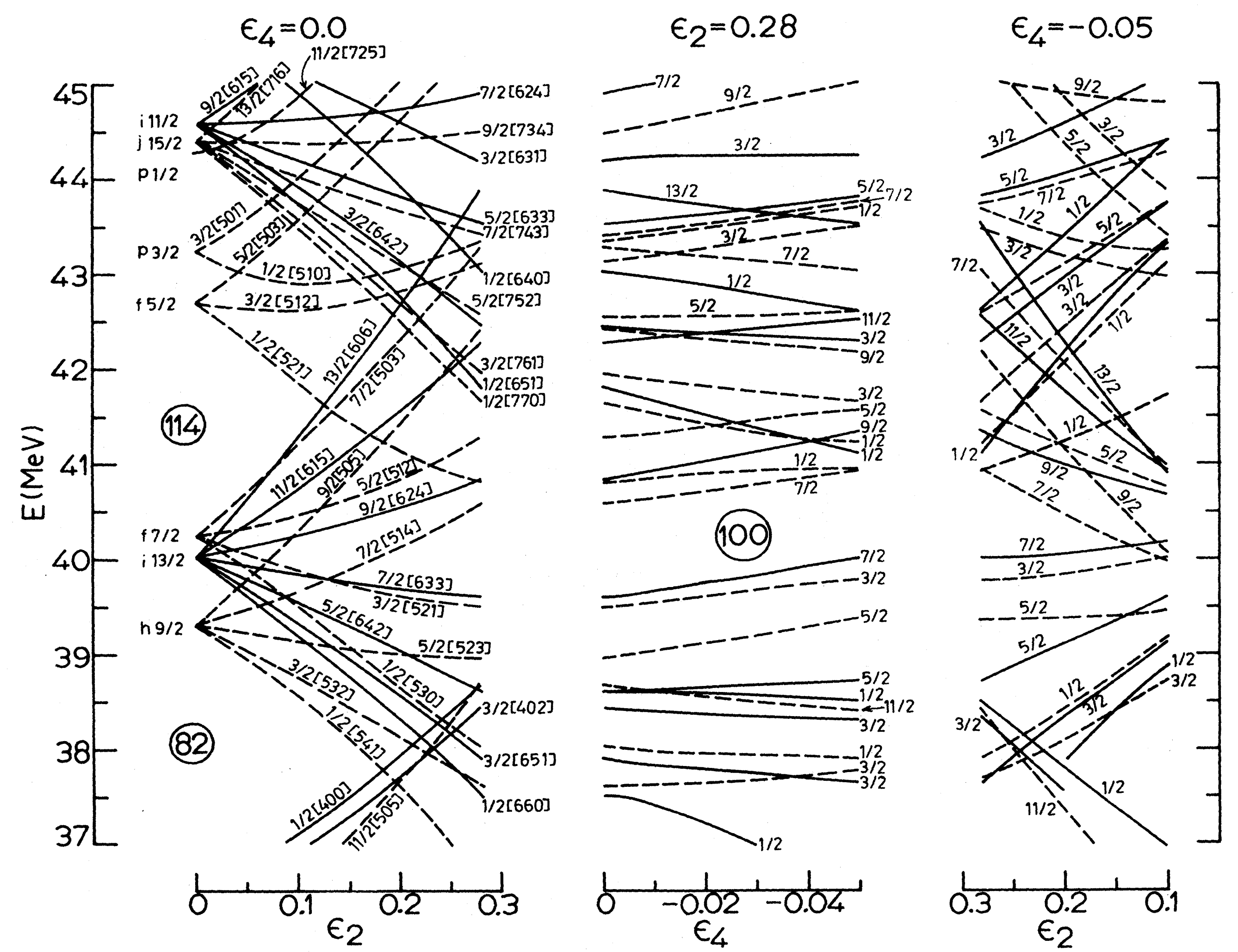

FIG. 7. Single-proton levels in the actinide region by using the MHO for $\epsilon_2=0$ to 0.28 with $\epsilon_4=0$, for $\epsilon_4=0$ to -0.05 with $\epsilon_2=0.28$, and for $\epsilon_2=0.28$ to 0.10 with $\epsilon_4=-0.05$. The parameters used are $\kappa=0.0577$ and $\mu=0.650$.

different sequences of intrinsic states in odd-A nuclei than those observed in the MHO of Nilsson in the region $219 \leq A \leq 229$. Although a similar result is expected in the rare-earth region, the necessary theoretical-experimental comparisons are not available. For this reason, experimental levels in the region of possible octupole deformation in the rare earths are compared with the Nilsson levels, and the other criteria, (1)–(5) in the preceding paragraph, are used to test for octupole deformation.

The first attempt to calculate actinide potential-energy surfaces in the $\epsilon_2\epsilon_3$ coordinates (Möller *et al.*, 1972) utilized the MHO and succeeded in obtaining a shallow octupole minimum, although of oblate nature, in the Ra isotopes. Later, Chasman (1979, 1980), using the Woods-Saxon (WS) potential, suggested octupole instability in a number of even-even and odd-A actinide nuclei.

In the actinide region it has been found that the coupling to octupole deformation is stronger in a potential with a more realistic flat-bottomed shape (Leander *et al.*, 1982). The folded Yukawa potential (FY) used by Leander *et al.* leads to an octupole coupling that is about 1.6 times stronger than that obtained with the MHO potential. The WS potential gives results very similar to those of FY (Nazarewicz, Olanders, Ragnarsson, Dudek, and Leander, 1984; Nazarewicz, Olanders, Ragnarsson, Dudek, Leander, Möller, and Ruchowska, 1984). A clear instability with respect to octupole deformation for nuclei around ^{222}Ra was noted for the first time in the FY potential (Möller and Nix, 1981). Later calculations (Leander *et al.*, 1982) using the FY potential revealed an octupole deformed minimum in the potential-energy surface that was 1–2 MeV deeper than the minimum in the MHO at the same deformation. In a very recent paper, Sobiczewski *et al.* (1988) showed that when the potential-energy surfaces are studied in a multidimensional space with independent β_2, β_3, β_4, β_5, β_6, and β_7 and β_8 minimizations, the octupole minimum is even deeper.

The FY single-particle levels for protons and neutrons

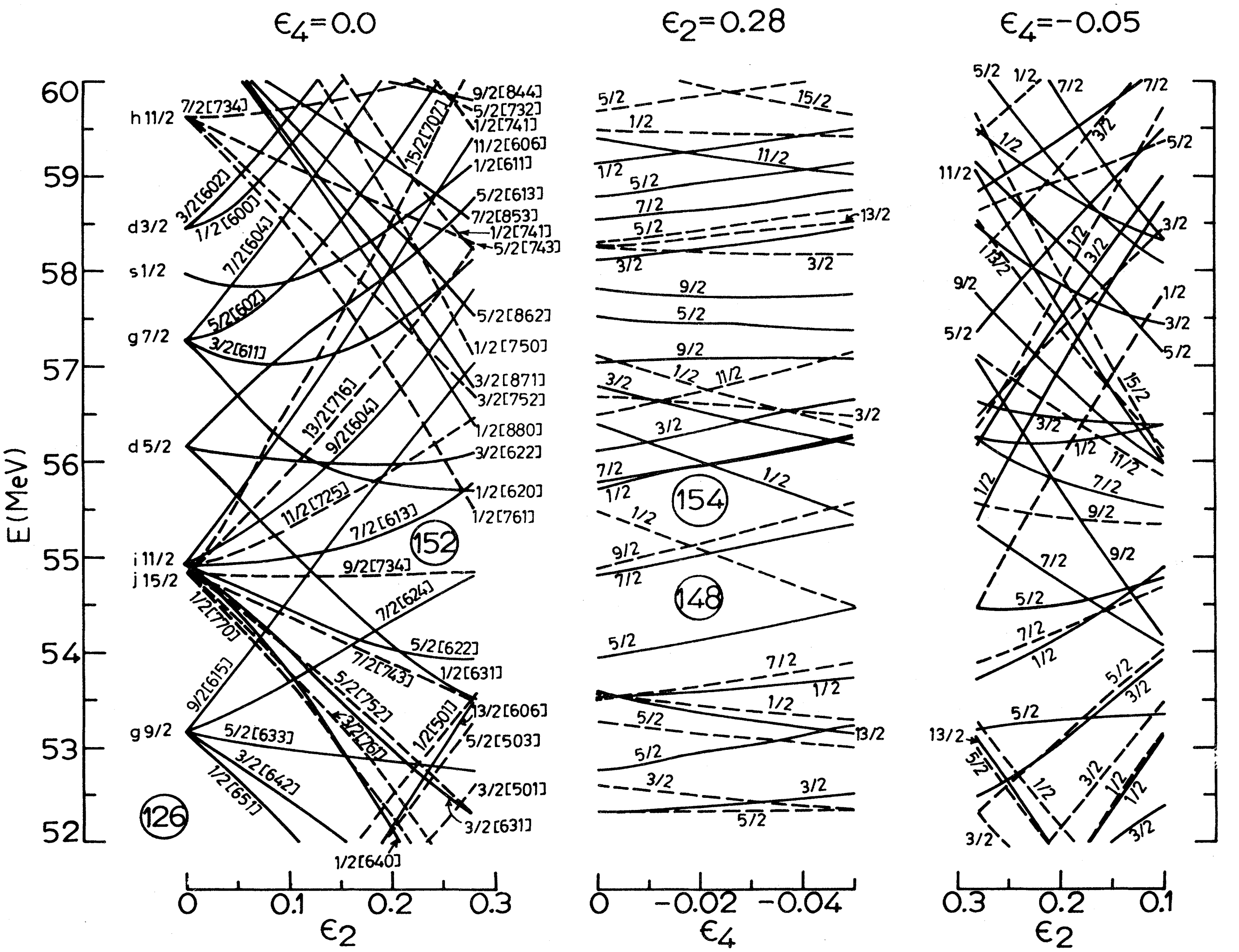

FIG. 8. Single-neutron levels in the actinide region by using the MHO for $\epsilon_2=0$ to 0.28 with $\epsilon_4=0$, for $\epsilon_4=0$ to -0.05 with $\epsilon_2=0.28$, and for $\epsilon_2=0.28$ to 0.10 with $\epsilon_4=-0.05$. The parameters used are $\kappa=0.0635$ and $\mu=0.325$.

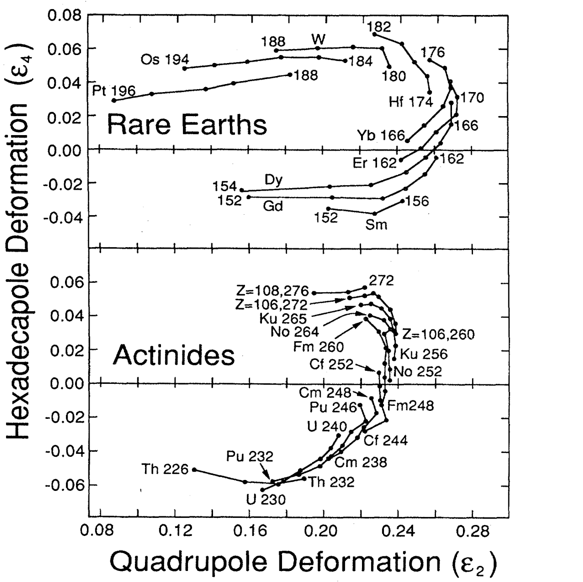

FIG. 9. Calculated ground-state deformations in the rare-earth and actinide regions in the ϵ_2–ϵ_4 space. From Nilsson *et al.* (1969).

calculated with a set of ^{226}Ra parameters (Leander *et al.*, 1982; Leander and Sheline, 1984) are respectively plotted in Figs. 10 and 11 as a function of the quadrupole deformation ϵ_2, for $\epsilon_3=0$ and 0.08. The nuclei in the region of ground-state octupole deformation, $85 \le Z \le 92$ and $131 \le N \le 139$, have ϵ_2 deformations that increase smoothly with increasing N and Z. The calculated octupole deformation in this region is $\epsilon_3 \approx 0.08$ to 0.10.

The left-hand sides of Figs. 10 and 11, corresponding to $\epsilon_3=0$, are labeled by the usual asymptotic quantum numbers. The single-particle levels for the asymmetric shape $\epsilon_3=0.08$, shown on the right-hand sides, are labeled by the projection quantum number Ω. In addition, the expectation values of some single-particle operators are indicated in parentheses. The first number is the expectation value $\langle \hat{s}_z \rangle$, which can be used in conjunction with Ω to calculate magnetic moments. The second number $\langle \hat{\pi} \rangle$ is the expectation value of the single-particle parity operator; it has a value between -1 and $+1$. It implies that the reflection-asymmetric Nilsson orbitals are strongly parity mixed. The third number $\langle a_p \rangle$, for $\Omega=\frac{1}{2}$ bands, represents a new decoupling parameter defined in the following section. These expectation

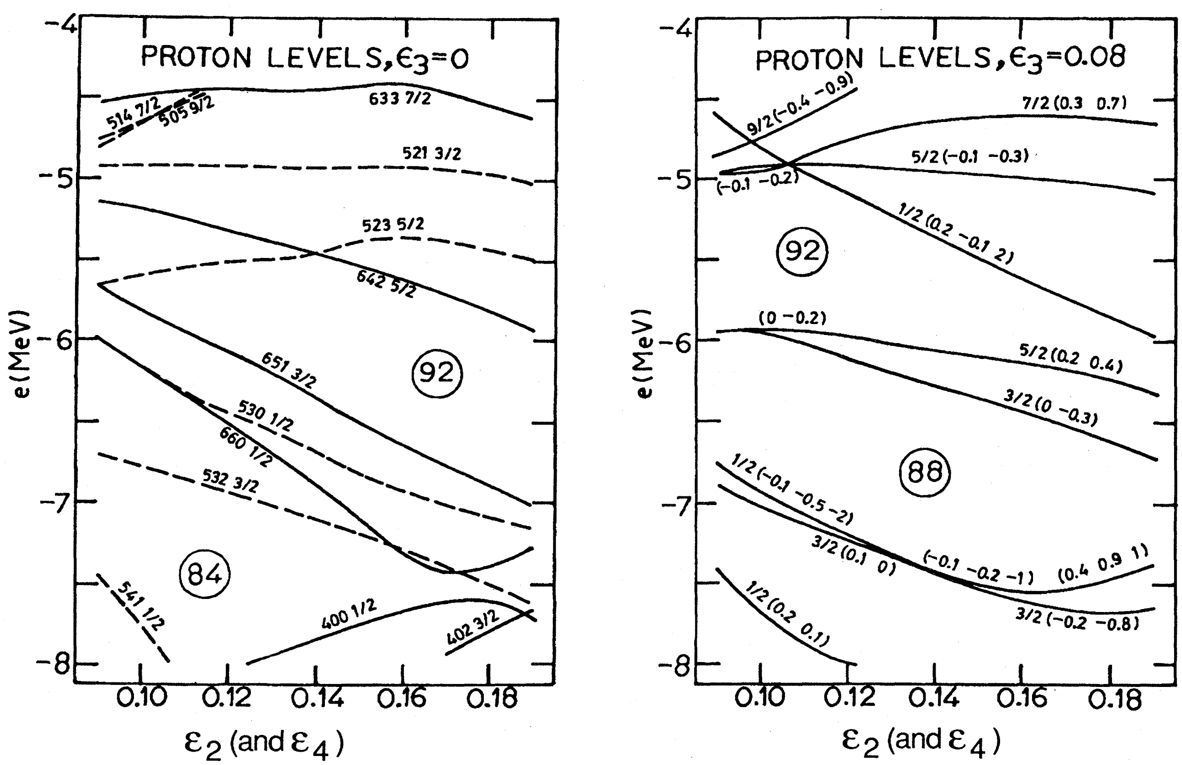

FIG. 10. Single-proton levels in the actinide region for a folded Yukawa (FY) potential with spheroidal symmetry, $\epsilon_3=0$, plotted vs the quadrupole deformation ϵ_2 (left-hand side). Asymptotic quantum numbers label the states. Shown on the right-hand side are single-proton levels in an axially symmetric, but reflection-asymmetric, folded Yukawa potential ($\epsilon_3=0.08$). The states are labeled by Ω; in parentheses are the matrix elements ($\langle \hat{s}_Z \rangle$, $\langle \hat{\pi} \rangle$, $\langle -j_+ \rangle \delta_{\Omega 1/2}$). See Sec. III.C for more discussion. The set of ϵ_4 values used is defined in Leander and Sheline (1984).

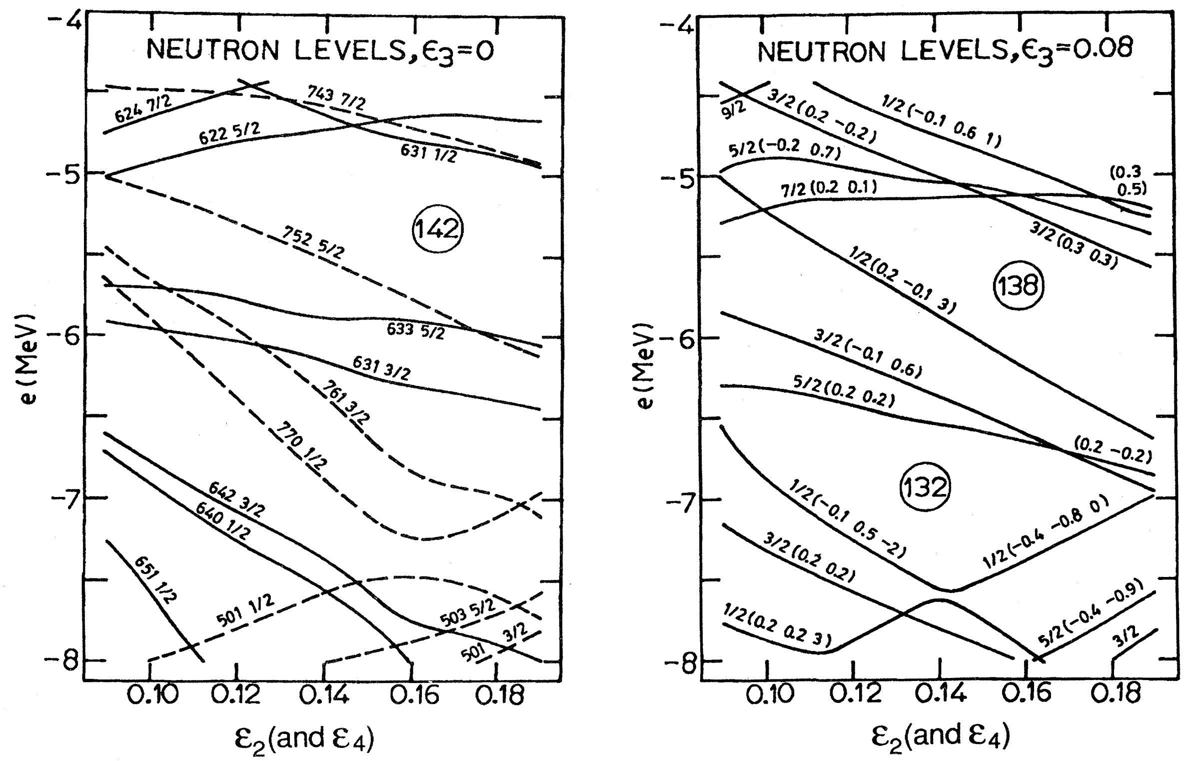

FIG. 11. Single-neutron levels in the actinide region for a folded Yukawa (FY) potential with spheroidal symmetry, $\epsilon_3=0$, plotted vs the quadrupole deformation ϵ_2 (left-hand side). Asymptotic quantum numbers label the states. Shown on the right-hand side are single-neutron levels in an axially symmetric, but reflection-asymmetric, folded Yukawa potential ($\epsilon_3=0.08$). The states are labeled by Ω; in parentheses are the matrix elements ($\langle \hat{s}_z \rangle$, $\langle \hat{\pi} \rangle$, $\langle -j_+ \rangle \, \delta_{\Omega\, 1/2}$). See Sec. III.C for more discussion. The set of ϵ_4 values used is defined in Leander and Sheline (1984).

values remain nearly constant over the variation of ϵ shown in the figures with deviations not exceeding ± 0.1 of the indicated values. However, these values are quite sensitive to variations in ϵ_3. A plot of single-neutron levels, shown in Fig. 12, illustrates the dependence on ϵ_3. The Nilsson levels for both MHO and FY potentials are shown in this plot. It is interesting to note that most of the details are common to both potentials.

Similar octupole deformed Nilsson diagrams obtained by using a WS potential have been presented recently by Leander and Chen (1988). Although the spherical single-particle energies of the WS potential used by Leander and Chen are slightly different from those of the FY potential described above, the level patterns are similar for the two models in the presence of (ϵ_2,ϵ_3) deformation. Figures 10 and 11, as we shall see in Sec. VIII, are very useful in the interpretation of odd-A energy-level data in the $A \sim 219$–229 mass region. Recently a paper was published that calculates the rare-earth single-particle levels in a quadrupole-octupole minimum (Cwiok and Nazarewicz, 1989a, 1989b). This investigation studies these levels in a multidimensional space in β_2, β_3, β_4, β_5, and β_6 and compares the predicted scheme with the experimental ground-state spins in odd-A Cs and Ba nuclei. These single-particle levels are plotted in Fig. 13 for both neutrons and protons. These levels are quite similar to an earlier set of levels (Leander *et al.*, 1985) that do not treat the higher deformations (ϵ_4, ϵ_5, and ϵ_6) as independent variables but as some combination of the lower deformations. It is clear that detailed comparisons between extensive level systematics will be necessary before the success of the model in the rare-earth region can be evaluated. It is also clear that these kinds of comparisons in the rare-earth and still lighter regions of the periodic table will be the subject of extensive additional research and of future reviews.

B. The rotational Hamiltonian

The rotational Hamiltonian is quite familiar and widely discussed by many authors (Bunker and Reich, 1971; Ogle *et al.*, 1971; Bohr and Mottelson, 1975; Engeland, 1984).

The total angular momentum I is composed of the rotational angular momentum R and the particle angular momentum J (only one valence particle coupled to the core). Thus

$$\mathbf{I}=\mathbf{R}+\mathbf{J}\ . \tag{3.13}$$

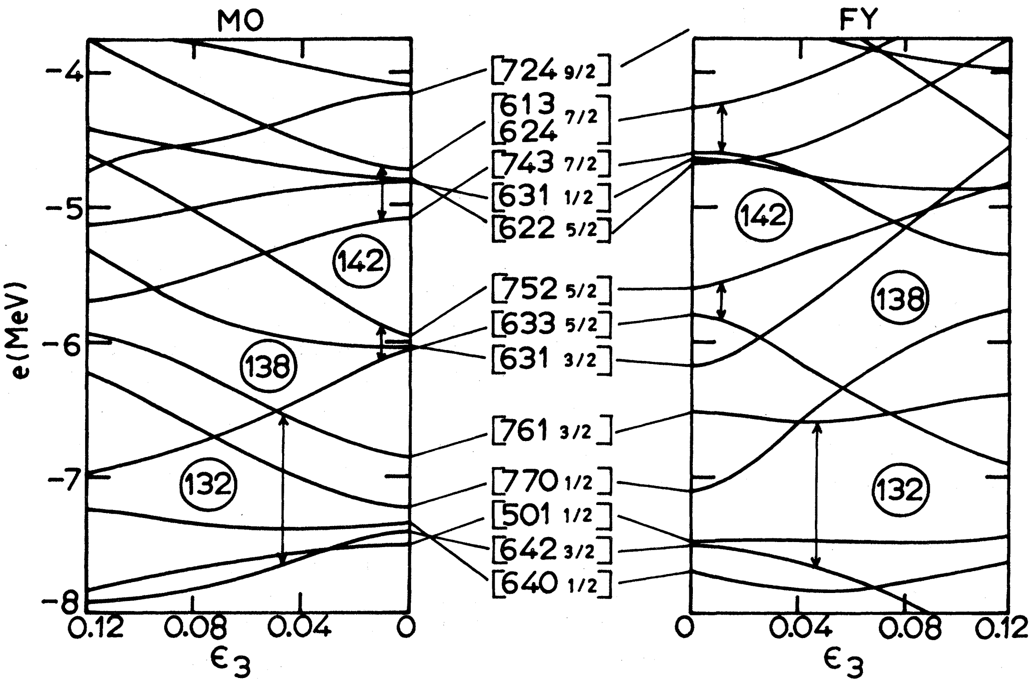

FIG. 12. Single-neutron levels plotted vs ϵ_3 (octupole deformation) in a MHO potential (left) and a FY potential (right). Other deformation parameters used are $\epsilon_2=0.15$, $\epsilon_4=-0.054$ and $\epsilon_2=0.16$, $\epsilon_4=-0.08$, respectively, corresponding to the equilibrium deformation for ^{226}Ra in the two different potentials. States that couple strongly via the Y_{30} operator are connected by arrows (Leander *et al.*, 1982).

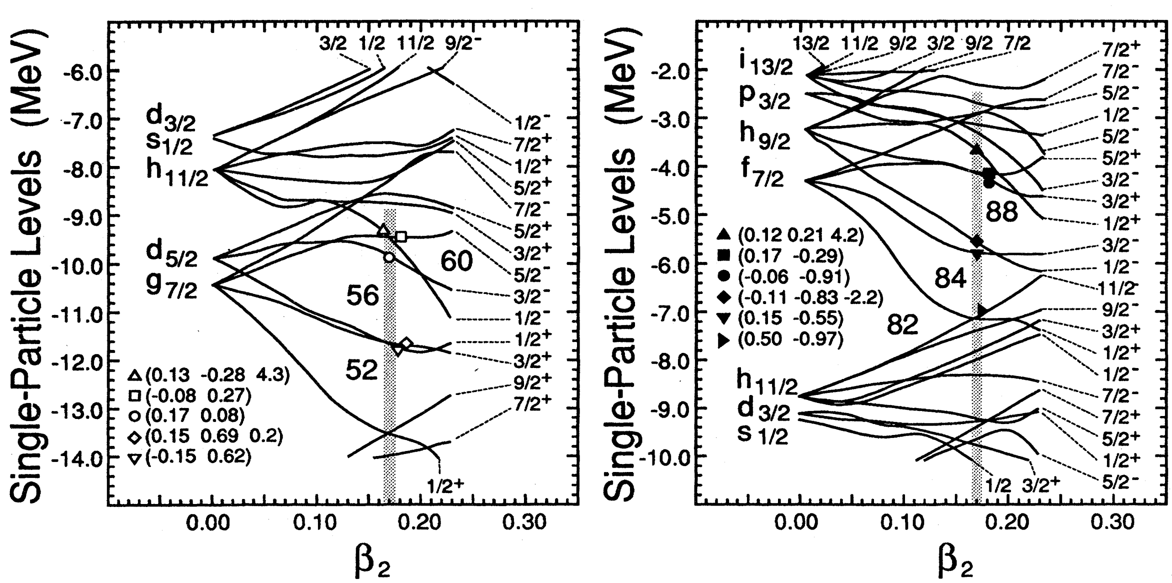

FIG. 13. Single-proton (left) and single neutron (right) levels in the rare-earth region plotted against β_2. The levels are calculated in a multidimensional space in β_2, β_3, β_4, β_5, and β_6 in which each of these variables is varied independently. Matrix elements for each level are given for $\beta_2=0.17$. The calculations are appropriate for the Cs–Ba region with $A\sim145$. Adapted from Cwiok and Nazarewicz (1989b).

For an axially symmetric rotor, the rotational Hamiltonian becomes

$$H_{\rm rot}=\frac{\hbar^2}{2\mathcal{J}}[(I^2-I_3^2)+(J^2-J_3^2)-(I_+J_-+I_-J_+)]\ , \tag{3.14}$$

where the middle term is the recoil term and the last term is the so-called Coriolis term or the rotation-particle coupling (RPC). The basis wave functions are given by

$$|IMK\rangle=\left[\frac{2I+1}{16\pi}\right]^{1/2}[D^I_{MK}\chi_K+(-1)^{I+K}D^I_{M,-K}\chi_{-K}]\ , \tag{3.15a}$$

where M is the projection of the nuclear spin I on a space-fixed axis, D^I_{MK} are the rotation matrices, and

$$\chi_K=\sum_{l\Lambda}a_{l\Lambda}|Nl\Lambda\Sigma\rangle \tag{3.15b}$$

are the eigenfunctions of $H_{\rm sp}$ expressed as linear combinations of the spherical harmonic-oscillator basis functions. Each intrinsic state $|K\rangle$ in odd-A deformed nuclei has associated with it a rotational band wherein the level energies of its $I=K,\ K+1,\dots$ members are approximately given by the adiabatic formula

$$E(I,K)=E_K+A[I(I+1)+\delta_{K,1/2}a(-1)^{I+1/2}(I+\tfrac{1}{2})]\ . \tag{3.16}$$

Here E_K is chosen to match $E(K,K)$ to the experimental bandhead energy, A is the inertial parameter proportional to the inverse moment of inertia, and a is the decoupling parameter for the $K=\frac{1}{2}$ bands; the last term arises from the nonvanishing first-order contribution of the Coriolis term for the $K=\frac{1}{2}$ bands only.

Of particular interest is the new reflection-asymmetric rotor-plus-particle model (Leander and Sheline, 1984; Leander and Chen, 1988). The new rotational Hamiltonian is

$$H_{\rm rot}=\frac{\hbar^2}{2\mathcal{J}}[(I^2-I_3^2)+(J^2-J_3^2)-(I_+J_-+I_-J_+)] +\tfrac{1}{2}E(0^-)(1-\hat{P})\ , \tag{3.17}$$

where an additional term appears involving the core parity operator $\hat{P}$. It reflects the empirical fact that the core has an additional set of states $R^\pi=1^-,3^-,5^-,\dots$, which are displaced upward by an amount $E(0^-)$. The core parity operator is given by

$$\hat{P}=\hat{p}\hat{\pi}\ , \tag{3.18}$$

where $\hat{p}$ is the total parity operator with an eigenvalue p, and $\hat{\pi}$ is the single-particle parity operator. The total Hamiltonian is diagonalized in the laboratory-frame basis states

$$\Psi_{IM\Omega p}=\frac{1}{2N}(1+\hat{R})D^I_{MK}(1+p\hat{P}\hat{\pi})\tilde{\chi}_{\nu\Omega}\ , \tag{3.19}$$

where N is a normalization constant and $\tilde{\chi}_{\nu\Omega}$ is the BCS state with the odd particle in the state $\chi_{\nu\Omega}$.

The first term in $H_{\rm rot}$ is diagonal with the eigenvalue $[I(I+1)-K^2]$. The second term in $H_{\rm rot}$, $(J^2-J_3^2)$, is a two-body operator, and its matrix elements and also other single-particle matrix elements may be found in the literature (Boisson and Piepenbring, 1971; Leander and Chen, 1987, 1988). The next term is the rotation-particle coupling term with the same off-diagonal matrix elements as in the reflection-symmetric case. The usual BCS pairing factor $(uu'+vv')$ is multiplied by the RPC term. However, further attenuation may sometimes be necessary. The diagonal RPC matrix elements for $K=\frac{1}{2}$ states also become identical to the reflection-symmetric case, if we define a new decoupling parameter a_p in the asymmetric case as

$$a_p=-p\langle\hat{\pi}\chi_{1/2}|\hat{j}_+|\hat{R}\chi_{1/2}\rangle\ . \tag{3.20}$$

Since the parity remains unchanged under particle-hole conjugation, the operator π in the BCS quasiparticle approximation has the value

$$\langle\hat{\pi}\rangle_{\rm BCS}=(uu'+vv')\langle\hat{\pi}\rangle_{\rm sp} \tag{3.21}$$

and determines the energy splitting $E_I^- - E_I^+$ within a parity doublet of the odd-mass system in the strong-coupling limit:

$$E_{I^-}-E_{I^+}=\langle\hat{\pi}\rangle E(0^-)\ . \tag{3.22}$$

Since $\langle\hat{\pi}\rangle$ lies between -1 and $+1$, depending on the amount of parity admixture, the odd-A parity splitting ranges from zero to the full core value $E(0^-)$.

C. Residual interactions

The MHO potential or other such mean-field potentials represent an averaged-out contribution of the nuclear forces and can explain the shell structure very well. However, small two-body forces, also known as the residual interactions, which are responsible for important modifications in the level properties, remain unaccounted for. The most important residual interactions are the well-known pairing interaction and the particle-hole interaction.

1. Pairing interaction

It is well known that the ground-state mass of an odd-A nucleus is always greater than that of its neighboring even-even nuclei. This empirical fact has been interpreted in terms of the short-range correlations among pairs of neutrons/protons occupying time-reversed orbitals. It is now understood that pairing correlations affect the level properties in many ways and also lower the moment of inertia of deformed nuclei from its rigid body value. On the suggestion of Bohr *et al.* (1958), the BCS theory of superconductivity (Bardeen *et al.* 1957) was applied to problems in nuclear structure by Belyaev (1959), Migdal (1959), Soloviev (1958/9), and Kisslinger and Sorensen (1960). Discussions of these applications can be found in many reviews and books (see, for example, Nathan and Nilsson, 1968; Bohr and Mottelson, 1969, 1975; Ogle *et al.*, 1971).

The most dramatic effect on the single-particle-level energies is a "compression" effect discussed by many authors (Ogle *et al.*, 1971; Chasman *et al.*, 1977). The single unpaired particle present in an odd-A system leads to the well-known "blocking" effect. As a result the effective pairing correlations are reduced. However, the effect is strongest when the Fermi level (the ground state) is blocked and decreases as higher-lying levels become blocked. In the state-independent pairing approximation, the effect of pairing may be taken into account by replacing the single-particle energy $e_{\nu\Omega}$ by a quasiparticle energy $\tilde{e}_{\nu\Omega}=[(e_{\nu\Omega}-e_f)^2+\Delta^2]^{1/2}$, where e_f is the energy of the Fermi surface and Δ is half the pairing energy. The lower-lying excitations are therefore considerably "compressed" in comparison to the value $|e_{\nu\Omega}-e_f|$ expected from the single-particle model; the compression is about 1.5 to 2 times. Accordingly we have reduced the calculated excitation energies by half in order to compare the theoretical and empirical systematics in Secs. VI and VIII.

2. Quasiparticle-phonon interaction

In addition to the short-range weak attractive pairing interaction discussed above, a long-range component of the residual interaction plays an important role in affecting the level properties of odd-A nuclei. This part of the residual interaction manifests itself in terms of a mixing of the one-quasiparticle state with the vibrational excitations (phonon) of the even-even core via multipole-multipole forces. The lowest vibrational states correspond to the first phonon excitation built on the one-quasiparticle states closest to the Fermi level. It is customary to characterize the phonon excitations in the even-even core by the quantum numbers λ and ν, where λ is the multipole order of the vibrational phonon and ν is the projection of λ on the symmetry axis. A vibrational state, based on a quasiparticle state having projection quantum number K_0, may have a resultant $K=|K_0\pm\nu|$. Thus two gamma-vibrational states corresponding to $K=|K_0\pm 2|$ are possible in odd-A nuclei. A large number of gamma-, beta-, and octupole vibrational states have been seen in odd-A rare-earth and actinide nuclei. However, there is sufficient evidence, both theoretical and experimental, that points to a mixing of the one-quasiparticle and the vibrational phonon excitations. The mixing effects are quite significant and may also be seen in the low-energy levels if the vibrational excitations occur at low energy.

The interaction between quasiparticles and phonons in deformed nuclei was first studied by Soloviev (1965) and by Bes and Cho Yi-Chung (1966). Detailed calculations of the energies of nonrotational states and the structure of these states for nuclei in the mass range $A=153$ to 175 have been reported by the Dubna group (Soloviev and Vogel, 1967; Soloviev *et al.*, 1967; Malov *et al.*, 1970). Similar calculations for the actinides have also been performed (Malov and Soloviev, 1967; Gareev *et al.*, 1971; Komov *et al.*, 1972). The microscopic structure of the vibrational states is taken to be a coherent linear combination of three-quasiparticle states. In each three-quasiparticle component state, one of the quasiparticles always occupies the base state on which the phonon excitation is based; the other two quasiparticles occupy states on opposite sides of the Fermi level (one is a particle; the other, a hole). It has been pointed out by Chasman *et al.* (1977) that the calculations of the Dubna group tend to overestimate the downward shift of low-lying single-particle states. Furthermore, these calculations do not properly take into account the Pauli principle. In spite of these deficiencies, the Dubna calculations remain the most extensive results of this type in the rare-earth and the actinide regions.

Calculations of Bes and Cho Yi-Chung (1966) in the rare-earth region remove some of the deficiencies, although these authors include only gamma-vibrational phonons in their treatment. Immele and Struble (1977a, 1977b) presented improved calculations on these counts for rare-earth nuclei. Coriolis interactions among phonon-admixed states have been considered by Kvasil *et al.* (1978), and detailed calculations have been presented for ^{161}Dy with good agreement. The problem of taking the Pauli exclusion principle into account has been examined by Soloviev *et al.* (1983). These calculations point out that the quasiparticle-plus-phonon states can be divided mainly into two groups. If the Pauli principle is not violated, or if it is weakly violated in the quasiparticle-plus-phonon components of the wave functions, then the corresponding vibrational states may be observed in odd-A nuclei. However, a strong violation of the Pauli principle results in a large upward shift of 1–2 MeV of the centroid energies. These states are then fragmented over several levels.

D. Other theoretical approaches to odd-A nuclei

Another formalism for interpreting the rotational band structure of even-even nuclei, known as the interacting boson model (IBM), was proposed in 1975 by Arima and Iachello (1976); it utilizes the group theoretical approach to exploit the dynamic symmetries of deformed nuclei. This led to an explosive amount of work, which has recently been reviewed by Iachello and Arima (1986) and Casten and Warner (1988). The IBM has now been extended to include an odd fermion, resulting in the interacting boson-fermion model (IBFM), to interpret the intrinsic states of odd-A nuclei (Iachello and Scholten, 1979; Bijeker, 1984). Considerable effort is now underway (Bijeker and Kota, 1988; Leviatan and Shao, 1989) to establish a correspondence between the dynamic symmetries of IBFM and the Nilsson model; a review of these new developments may be found in Elliott (1985) and Van Isaker (1988). Some calculations have been performed successfully for a few odd-A rare-earth nuclei. This approach, aimed at providing a deeper understanding of the intrinsic states and their classification in terms of symmetry groups, is not presently in a sufficiently developed stage and therefore is not discussed in detail in this review.

Using a more self-consistent approach to the calculation of the spectroscopic properties of odd-A deformed nuclei, Libert and Quentin (1982) presented the Hartree-Fock plus BCS calculations with the phenomenological Skyrme III interaction. They obtained single-particle Hartree-Fock energy-level diagrams similar to the Nilsson diagrams for the actinide region. A comparison of the calculations with the experimental spectroscopic data for 23 odd-A actinide nuclei was quite satisfactory (Libert *et al.*, 1982). These calculations, by far the most extensive of their kind, represent an important step in improving the formalism of the phenomenological rotor-plus-quasiparticle calculations, as they do not contain any *ad hoc* parameters except the six force parameters. Although several investigations of odd-A rare-earth nuclei using the HFB approach have been reported (see, for example, Ansari, 1986, and Sarriguren *et al.*, 1989), no similar survey of this region is presently available. This approach needs to be further refined, and calculations pursued more vigorously, in the rare-earth and the actinide regions.

It may, however, be pointed out that the Hartree-Fock method is not just another theoretical approach. Because of its more fundamental microscopic nature and its self-consistency, the close agreement between the Hartree-Fock and the Nilsson-model results provides a significant justification for this and similar, more phenomenological, approaches.

IV. METHODS USED FOR DEDUCING INTRINSIC-STATE CONFIGURATIONAL ASSIGNMENTS

The configurational assignments summarized in Secs. V and VII are taken from the literature. The methods used in these assignments have been detailed in the two previous reviews on the rare earths and the actinides (Bunker and Reich, 1971; Chasman *et al.*, 1977). Therefore we summarize them briefly, emphasizing only those aspects that represent recent developments. We begin with the assumption of a more or less detailed set of levels with assigned spins and parities. We leave to previous reviews all discussion of spin-parity assignments involving a variety of decay and nuclear reaction studies and their auxiliary methodology.

A. Comparison of the theoretical and experimental energy systematics

Sections VI and VIII of this review make it quite clear that the most powerful general technique of making configurational assignments is by the comparison of the energies of experimental rotational bands with the energies predicted for configurations in the Nilsson model and its variations, outlined in Sec. III. Experimental limitations of this method include the possibility of highly perturbed bands, the uncertainty in particle-hole character for bands near the ground state, and the incomplete nature of the data. Among the theoretical limitations are the difficulty of including vibrational components in the wave functions and the uncertainty of the appropriate model, particularly in the transition regions where the various model variations overlap. This problem is especially severe in the actinide region with $A \sim 229$, because of the coexistence of reflection-symmetric and reflection-asymmetric shapes and their corresponding spectroscopies.

B. Favored alpha decay

The alpha decay hindrance factor (HF), defined (Lederer and Shirley, 1978) as the ratio of the experimental partial alpha half-life to the interpolated unhindered alpha half-life, is particularly useful in those cases in odd-A nuclei where its value is between 1 and 4. In these favored alpha transitions (Rasmussen, 1954), the unpaired nucleon in the ground state of the parent nucleus remains unchanged in the daughter nucleus. Therefore a definite configurational assignment can be made if the other state involved in the alpha transition has already been characterized. In the case of reflection asymmetry in odd-A nuclei, the opposite parity members of a parity doublet are just different projections of the same intrinsic state of broken reflection symmetry. Then favored alpha decay to both parities should occur. This quite new use of favored alpha decay has been demonstrated for ^{223}Ac, ^{225}Ac, and ^{227}Ac (Leander and Sheline, 1984). However, in all three cases the HF to the state of opposite parity, while quite small, is from 2.8 to 15 times the HF to the state of the same parity.

C. Allowed unhindered beta decay

Beta decay (β^-, β^+, EC) reduced transition probabilities are usually expressed in terms of $\log ft$ values. While they provide much useful information in assigning spins and parities, for the most part they are not useful in assigning configurations in odd-A nuclei. However, in the odd-A rare-earth nuclei, spin-flip transitions $n{:}5/2^-[523\downarrow] \rightleftarrows p{:}7/2^-[523\uparrow]$ and $n{:}7/2^-[514\downarrow] \rightleftarrows p{:}9/2^-[514\uparrow]$ can be identified by their allowed unhindered (au) $\log ft \leq 5.2$. A recent exhaustive survey (Sood and Sheline, 1989b) of these β decays has revealed evidence for au transitions involving two other configuration pairs, $n:3/2^-[532\downarrow]\rightleftarrows p:5/2^-[532\uparrow]$ and $n:9/2^-[505\downarrow]\rightleftarrows p:11/2^-[505\uparrow]$, in even-$A$ nuclei. It will be of interest to look for these [532] and [505] spin-flip transitions in odd-A rare-earth nuclei. No *au* transition has so far been observed in the actinide region.

D. Transfer reactions

One of the most powerful techniques of identifying configurations in odd-A nuclei utilizes nuclear reaction spectroscopy and single-nucleon transfer reactions, such as (d,p), (d,t), $(^3\text{He},d)$, $(^3\text{He},\alpha)$, and (α,t), and the inverse of these reactions (Vergnes and Sheline, 1963). The success of the method depends on the fact that simple first-order theory predicts with a reasonable degree of correctness the differential cross sections for populating the various members of a rotational band (see, e.g., Bunker and Reich, 1971, and Chasman *et al.*, 1977). Since different rotational levels are usually populated with quite different intensities, each configuration has its own characteristic set of band intensities or "fingerprint." Although second-order processes affect particularly the weaker intensities in the "fingerprint," the method has proved to be very useful. Multinucleon transfer reactions such as (α,d), (α,p), $(^3\text{He},p)$, and (t,p), and the inverse of these reactions, have a much more limited usefulness in assigning configurations because the theory predicting cross sections is in a less satisfactory state.

E. Decoupling parameters in $K=\frac{1}{2}$ bands

The decoupling parameter is normally indicative of given $K^\pi=1/2^\pm$ configurations and is predicted by the Nilsson model and its variations. Consequently it serves as an aid in classifying configurations. The decoupling parameters of $K^\pi=1/2^\pm$ parity doublet bands in quadrupole-octupole deformed nuclei are expected to approach the same absolute values, but with opposite sign. They can be calculated confidently in the rigid asymmetric model (Leander and Sheline, 1984) and differ significantly from calculated values from the Nilsson model without reflection asymmetry. The vibrational components in $K=1/2$ bands also affect the values of decoupling parameters.

F. Magnetic moments

The great increase in the available data on magnetic moments, not only for ground states but also for excited states (Raghavan, 1989), allows a corresponding increase in its use in assigning configurations. These magnetic moments for different configurations can be calculated using the Nilsson model and its variations and compared with experiment (Bengtsson *et al.*, 1989). However, since parity doublets in reflection-asymmetric nuclei are just different projections of the same intrinsic state, the magnetic moments of the parity doublets are expected to approach the same value, which, in general, is quite different from that predicted by the Nilsson model without reflection asymmetry.

V. EMPIRICAL DATA ON INTRINSIC STATES IN THE MASS REGION ($151\leq A\leq 193$)

A. Introduction to data tables

The empirical data on the intrinsic states in the rare earths is summarized in Tables II–XXIII (below). We have also included in our review the $N=88$ (odd-Z) and $N=89$ (even-Z) nuclei. Since the deformation sets in rather abruptly between $N=88$ and 90, the Nilsson configurations of levels in these nuclei are not expected to be as pure. However, their inclusion is significant in that they allow us to understand the complexities of the transition region and also the collapse of Nilsson orbitals into shell-model states. On the other end of our mass region, we have included ^{187}W, ^{189}Os (both $N=113$), ^{191}Os ($N=115$) and ^{193}Os ($N=117$) where Nilsson assignments have been made.

The levels included in these tables are the single-particle excitations, mixed vibrational excitations, and the pure vibrational excitations. The data on three- and other multiquasiparticle states are presented separately. This compilation represents a phenomenal growth in data over the last such compilation, presented by Bunker and Reich (1971). There are three types of assignments: firm assignments, probable assignments (enclosed in parentheses), and tentative assignments (discussed in the footnotes). The probable assignments result mostly from an experimental uncertainty in the spin of the level. Changes in configuration assignments from earlier reviews are pointed out in the footnotes.

The organization of the tables deviates considerably from the earlier reviews of Bunker and Reich (1971) and Chasman *et al.* (1977). One table for one nuclide would have resulted in 120 tables for the mass region $151\leq A\leq 193$ and 55 tables for the mass region $A\geq 221$. A global organization of the data therefore became necessary. In addition to concise presentation, such a global view is more revealing, and therefore useful, in discussing the systematics and trends and in highlighting presently unobserved levels. In this presentation some information (such as the reaction citations for each individual level, half-life, etc.) could not be included. However, this may be looked up, if needed, in recent *Nuclear Data Sheets*, the *Table of Isotopes* (Lederer and Shirley, 1978), or the individual data tables for each nucleus prepared by us (Jain *et al.*, 1989a, 1989b).

Tables II–X contain the data for odd-Z isotopic chains from $Z=61$ to 77, and Tables XI–XXII contain the data for odd-N isotonic chains from $N=89$ to 111. The data for $N=113$, 115, and 117 nuclides are presented in Table XXIII.

The first column of each table lists the configuration of

TABLE IIff. In Tables II through XXIII (for rare earths) and XXXI through XLII (for actinides), we list the intrinsic states (including the single-particle, vibrational admixed, and pure vibrational configurations) in the odd-mass deformed nuclei. The first column lists the Nilsson configuration of each state, in terms of the asymptotic quantum numbers $K^{\pi}[Nn_z\Lambda]$, occurring in the nuclide (listed in the top row) of the specified isotopic/isotonic sequence; the vibrational excitations or their admixtures are denoted by the base-state configuration coupled to the specific phonon excitation. For each configuration in every nucleus, the data entries include, in the top subrow, twice the spin in parentheses ($2I$) *only* for those cases where $I \neq K$, followed by the observed level energy (in keV); the middle subrow includes, on the left, the moment-of-inertia parameter A (in keV) derived from the first two rotational level energies (unless mentioned otherwise) and rounded off to the first decimal place, and, on the right, the decoupling parameter a for the $K=1/2$ bands derived from the first three rotational level energies (unless mentioned otherwise) and rounded off to two decimal places; the bottom subrow lists the logft values for the beta transitions feeding the level, that for β^- on the left and for β^+/EC on the right. The parentheses around an entry denote not-so-definite assignment/parameter value. A subscript "iso" to the energy value denotes an isomer with half-life above the arbitrarily chosen limit of 1 μsec. A similar subscript "iso" to the logft value denotes beta decay of an isomer. A subscript α to the energy values for actinides in Tables XXXI through XLII denotes a favored alpha transition. The tentative/speculative configuration assignments are not listed in the main body of the table, but are included in the footnotes referred to in the last row of the main table. The references to the experimental data for each nuclide are given as footnotes with entries arranged sequentially to include the most recent Nuclear Data Sheets (NDS), the beta decay, and the reaction studies. Other footnotes include references to conflicting assignments, theoretical considerations, and/or level energy of $I=K$ state, if known, for cases wherein the lowest rotational level has $I \neq K$, and other comments of interest in specific cases. Table II lists the data for $Z=61$ nuclei.

$_{61}$Pm	$A=151^{a,i}$		153^{b}	
5/2$^+$[413]	0		32	
	12.1		10.7	
3/2$^+$[411]	255.7		453	
	13.6		11.6	
	6.9			
7/2$^+$[404]	781.0			
1/2$^+$[411]	852.3^{c}			
	15.4	−0.48		
	7.8			
5/2$^-$[532]^{d}	116.7		0	
	8.3		9.4	
	7.2			
1/2$^+$[420]	426.4		707	
	14.4	1.22	12.5	1.35
	7.2			
3/2$^-$[541]	540.2		935^{e}	
			17.4	
	7.0			
3/2$^+$[422]			1208	
			10.8	
Other levels	f,g		h	

[a]Singh *et al.* (1988): NDS; Seo *et al.* (1973), Iimura *et al.* (1985): decay, Burke and Waddington (1972): (^{3}He,d), (α,t), (t,α); Straume *et al.* (1979): (t,α).

[b]Lee (1982): NDS; Burke *et al.* (1978): (t,α); Sugarbaker (1977): (d,^{3}He).

[c]The 852-keV level proposed as 1/2$^+$[411] by Straume *et al.* (1979) was not observed in decay by Iimura *et al.* (1985). Calculations, however, support the existence of this band as mainly {5/2$^+$[413]$\otimes$2$^+$} (53%) rather than 1/2$^+$[411].

[d]Belongs to the $h_{11/2}$ proton orbital and therefore is a strongly Coriolis-coupled band, thus destroying normal $I(I+1)$ behavior.

[e]Observed $d\sigma/d\Omega$ for this peak is larger than expected for the 3/2$^-$[541] state, so Burke *et al.* (1978) attributed part of the intensity to the 9/2$^+$ member of the 1/2$^+$[420] band. In addition 3/2$^-$[541] and 3/2$^+$[422] orbitals are expected to mix strongly with the 1/2$^-$[550] and 1/2$^+$[431] states, respectively.

[f]Burke and Waddington (1972) have observed strongly populated levels at 876, 916, and 959 keV, which remain unassigned. Straume *et al.* (1979) have tentatively proposed members of the 3/2$^+$[422], 5/2$^+$[402], and 3/2$^-$[541] bands at 940 keV (7/2$^+$), 913 and 956 keV (fragmented), and 642 keV (11/2$^-$), respectively. Also proposed are members of 1/2$^-$[550] and 7/2$^-$[523] bands at 746 keV (3/2$^-$) and 1205 keV (11/2$^-$), respectively.

[g]Comment: Lee *et al.* (1981) studied ^{152}Sm(d,^{3}He)^{151}Pm, measured angular correlations, and identified peaks with groups of levels having all the above Nilsson configurations.

[h]A large peak is observed by Burke *et al.* (1978) at 1179 keV, but it is not assigned. Many other peaks above 1400 keV also remain unassigned.

[i]^{151}Pm is probably octupole deformed (Sood and Sheline, 1989a; see Fig. 27).

TABLE III. Intrinsic states of $Z=63$ odd-*A* nuclei.

$_{63}$Eu	$A=151$[a,f]	153[b,g]	155[c,g]	157[d]	159[e]
$5/2^+[413]$	260.5[h] 9.16	0 11.9 7.28 8.56	0 11.2 ≥ 7.6	0 10.9	0 10.7
$3/2^+[411]$		103.2 13.9 6.75 7.72	245.7 12.3 6.72	394.2 11.8	333.6 11.0
$1/2^+[411]$			876.8 13.5 −1.29 8.59	(3) (975)	
$7/2^-[523]$					(1051.8)
$7/2^+[404]$	21.5 9.1 7.3	569.0 15.9	978		
$5/2^-[532]$		97.4 7.7 8.65 7.77	104.3 9.2 5.54	197.8 9.3	189.8 9.3
$3/2^-[541]$		636.5 9.1	768.5 9.8 7.13		
$1/2^+[420]$		634.6 11.5 1.43	923.2 8.6 2.14 8.67	(1057)[i] 14.6 1.0	1076 10.6 1.0
$5/2^+[402]$	$0(d_{5/2}^{-1})$[f] 7.5 8.2	706.6 17.1			
$1/2^-[550]$			(3) 1102[j] 15.4 −1.11		
$11/2^-$ ($h_{11/2}$)	196.2[k]				
$5/2^+$ $\{5/2^+[413]\otimes 0^+\}$		617.9	979.5		
$3/2^+$ $\{3/2^+[411]\otimes 0^+\}$			1064.6		
Other levels		l	m		n

[a]Singh *et al.* (1988): NDS; Bianco *et al.* (1979), Taketani *et al.* (1976): $(p,2n\gamma)$; Straume, Løvhøiden, and Burke (1976): (α,t), $(^3\text{He},d)$; Thun and Miller (1972): Coul.; Bernstein *et al.* (1970): (d,d'); Taketani *et al.* (1975): (p,t).
[b]Lee (1982): NDS; Burke *et al.* (1976): (t,p); von Egidy *et al.* (1985), Muhlbauer (1970): (n,γ); Dracoulis *et al.* (1975): $(d,3n\gamma)$; Thun and Miller (1972): Coul.; Sergienko and Lebedev (1974): EC; Bondarenko *et al.* (1984); $(n,n'\gamma)$, $(p,2n\gamma)$.
[c]Lee (1987): NDS; Ungrin *et al.* (1969): decay; Katajanheimo, Liljavirta, *et al.* (1984): $(^3\text{He},d)$; Prokofjev *et al.* (1986): (n,γ); Burke *et al.* (1976): (t,p); Burke, Løvhøiden, Straume, *et al.* (1979): $(\mathbf{t},\alpha)$.
[d]Helmer (1988): NDS; Kaffrell (1973): decay; Burke, Løvhøiden, Flynn, and Sunier (1979): $(\mathbf{t},\alpha)$.
[e]Lee (1988): NDS; Willmes *et al.* (1987): decay; Burke, Løvhøiden, Flynn, and Sunier (1979): $(\mathbf{t},\alpha)$.
[f]An analysis of (p,p') scattering data by Lanier *et al.* (1978) suggests $\beta_2=0.13$ for ^{151}Eu. Muonic x-ray studies done by Tanaka *et al.* (1984) also suggest quadrupole moment values that are many times the single-particle estimates for the first excited $7/2^+$ state and the $5/2^+$ state. An analysis of (d,p), (d,t) data by Lanier *et al.* (1980), however, suggests three distinct shapes in ^{151}Eu—a spherical shape for the ground state, moderately deformed for the $5/2^+$ state, and strongly deformed for the states between ~ 2.3 and 2.8 MeV. A particle-rotor-model calculation using the Nilsson model by Dracoulis and Leigh (1976), however, concludes that the ground state

TABLE III. (*Continued*).

is the $5/2^+$ member of a severely distorted $3/2^+[411]$ rotational band for a weakly deformed rotor having $\beta_2 \sim 0.16$.

[g]Octupole deformation in this nucleus is suggested (Sheline and Sood, 1990a) on the basis of the reversal of the phase of odd-even staggering of differential radii of the Eu isotopes ($N=88$ to 93) and observation of parity doublets connected by enhanced E1 transitions in ^{153}Eu and ^{155}Eu.

[h]Taketani *et al.* (1975) tentatively identify other members of this band at 414($7/2^+$) and 597 keV ($9/2^+$). They also suggest a vibrational state $\{5/2^+[413]\otimes 0^+\}$ at 654 keV and its $7/2^+$ member at 801 keV.

[i]Based on the expectation that the decoupling parameter for this $K=1/2$ band is ≈ 1, the $I=3/2$ and $I=5/2$ members of this band are expected to have nearly the same energy. Burke, Løvhøiden, Flynn, and Sunier (1979) assigned these band members to a proposed 1145-keV doublet. The observed cross section and analyzing power for the 1145-keV peak are consistent with this interpretation. See text for a full discussion of $K=\frac{1}{2}$ bands with $a=1.0$.

[j]The 1/2 level of this band lies at 1107 keV.

[k]Decoupled band. Straume, Løvhøiden, and Burke (1976), using (^{3}He,d) and (α,t) reactions, reported a strongly populated and low-lying 11/2 state which perhaps is the $11/2^-$ isomer observed at 196.2 keV in the ^{151}Gd decay by Voth *et al.* (1983). Straume and his colleagues (1976) also report a strong population of a $7/2^-$ level located at ≤ 50 keV above the $11/2^-$ state, which is contrary to the expectations based on the simple shell model, as there are no $f_{7/2}$ states in the $50<Z<82$ shell.

[l]Von Egidy *et al.* (1985) observed many other unassigned levels above 700 keV.

[m]Prokofjev *et al.* (1986) tentatively proposed the assignments $\{7/2^-, 7/2[523]\}$, $\{5/2^+, 5/2[402]\}$, and $\{3/2^+, 3/2[422]\}$ to levels at 1008 keV, 1231 keV, and 1483 keV, respectively. The fragmentation of the $5/2^+[402]$ configuration between the levels of 1230 and 1480 keV is discussed by Burke, Løvhøiden, Straume, *et al.* (1979).

[n]Angular distribution of Burke, Løvhøiden, Flynn, and Sunier (1979) suggests $I=3/2$ for a level at 806 keV, which may be a probable member of the $1/2^+[411]$ band.

TABLE IV. Intrinsic states of $Z=65$ odd-*A* nuclei.

$_{65}$Tb	$A=153$[a]	155[b,g]	157[c]	159[d]	161[e,h]	163[f]
$3/2^+[411]$	147.5 18.6 8.2	0 13.1 8.0	0 12.1 7.2	0 11.6 6.73 7.23	0 11.2	0 11.4
$7/2^+[404]$	80.7[i] 27.1 7.1	466.9	658.6	778		
$7/2^-[523]$		545.3 15.8 8.72	571.7 15.3	548.3 14.5	417.2 7.9 4.9	(343) 9.7[j]
$1/2^+[411]$ $+\{3/2^+[411]\otimes 2^+\}$		517.6	(597.8)[k] 12.6 0.04 $\sim$8.3	(580.9)[l] 11.8 0.04		
$1/2^-[541]$		863.0 10.2 1.86		(856)	(922) 9.5 2.42	
$5/2^+[402]$	$0(d^{-1}_{5/2})$[m] 36.3 6.69	501.0	837	(1020)	(1252.4) 7.3	
$1/2^+[411]$				(972.0) 11.9 −0.83		
$5/2^+[413]$	218.6 8.02	271.0 9.1 9.1	327.6 11.5	348.2 11.5 8.42 8.27	314.9 11.5 6.2	(396.4) 9.8
$5/2^-[532]$[n] ($h_{11/2}$)		227.0 6.25	326.4 5.45	363.6 6.76 $\leq$6.7	480.1 15.1 6.0	 19.6
$3/2^-[541]$		891.1 7.07				(1066) 13.3

TABLE IV. (*Continued*).

$_{65}$Tb	$A=153$[a]	155[b,g]	157[c]	159[d]	161[e,h]	163[f]
$1/2^+[420]$						(1226)[o] 10.9 0.96
$3/2^+[422]$					13.7	(1818)[p]
$11/2^-$ $(h_{11/2})$	$(16.3)^{q}_{iso}$ 28.6 8.0					
$1/2^+$ $\{3/2^+[411]\otimes 2^+\}$		508.5 7.92			517 11.3 0.20	
$3/2^+$ $\{3/2^+[411]\otimes 0^+\}$		743.9 8.38	992.8[r] 10.3 ~8.34			
$5/2^-$ $\{5/2^-[532]\otimes 0^+\}$		1062.1 7.43				
Other levels	s			t	u	v

[a]Lee (1982): NDS; Harmatz and Handley (1972): decay, (α,xn); Devous and Sugihara (1977): decay; Straume, Løvhøiden, and Burke (1976): $(^3\text{He},d)$, (α,t); Winter *et al.* (1978): $(\alpha,2n\gamma)$, $(\alpha,4n\gamma)$; Devous and Sugihara (1978): $(\alpha,4n\gamma)$.

[b]Lee (1987): NDS; Harmatz and Handley (1972), Abdurazakov, Vylov, *et al.* (1980): decay; Bengtsson *et al.* (1982): $(^{11}\text{B},4n\gamma)$, $(^{11}\text{B},6n\gamma)$; Winter *et al.* (1971): $(\alpha,2n\gamma)$, $(d,2n\gamma)$, $(p,n\gamma)$; Boyno and Huizenga (1972), Tippett and Burke (1972): $(^3\text{He},d)$, (α,t); Barat and Treherne (1973): $(p,5n\gamma)$.

[c]Helmer (1988): NDS; Blichert-Toft *et al.* (1967): decay; Boyno and Huizenga (1972), Tippett and Burke (1972): $(^3\text{He},d)$, (α,t); Winter *et al.* (1971): $(d,2n\gamma)$, $(p,n\gamma)$; Goles *et al.* (1972): (p,t).

[d]Lee (1988): NDS; Brown *et al.* (1969): decay; Chapman *et al.* (1983), Van Hove *et al.* (1984): Coul.; Tippett and Burke (1972), Boyno and Huizenga (1972): $(^3\text{He},d)$, (α,t); Winter, Funke, *et al.* (1974): $(p,2n\gamma)$; Felsteiner and Lindeman (1973): $(n,n'\gamma)$.

[e]Helmer (1984): NDS; Gasser *et al.* (1975): decay; Tippett and Burke (1972), Boyno and Huizenga (1972): (α,t), $(^3\text{He},d)$; Sterba *et al.* (1976): (t,α).

[f]Burrows (1989): NDS; Sugarbaker (1977): $(d,^3\text{He})$.

[g]This nucleus probably has some octupole deformation.

[h]Except for the ground-state band, the level energy data of Boyno and Huizenga (1972) are systematically smaller than those of Gasser *et al.* (1975) and Tippett and Burke (1972). If they are increased by 8 keV, a fair agreement is obtained in the energy range 300–1450 keV. The cross sections and intensity ratios of Boyno and Huizenga also show unreasonable behavior. Moreover, except for $3/2^+[411]$ and $5/2^+[413]$ bands, the band assignments of Sterba *et al.* (1976) differ from those adopted here.

[i]Devous and Sugihara (1977) assigned $7/2^+[404]$ to a level at 254.2 keV and considered the 80.7-keV level as a band member of the ground-state band. However, population patterns of (HI,xn) reactions clearly show that 80.7 keV is the bandhead (Winter *et al.* (1978).

[j]The moment-of-inertia parameter evaluated from 7/2 (343 keV) and 11/2 (537 keV) levels.

[k]Calculations of Bes and Cho Yi-Chung (1966) and Soloviev and Vogel (1967) predict two $K=1/2^+$ states, the first at about 500 keV being ~50% single-particle and the second at about 1000 keV having no single-particle character. The two $1/2^+$ levels have been observed at 598 and 924 keV, but their characters do not match with theoretical predictions and their structure seems to be more complex (see Boyno and Huizenga, 1972).

[l]Calculations of Soloviev (1976) indicate that this state is 64% single-particle in character. Bunker and Reich (1971) have argued that this band should be primarily $\{3/2^+[411]\otimes 2^+\}$ with very small single-particle admixture.

[m]The ground state of this $N=88$ nucleus, like ^{151}Eu, is most likely a spherical shell-model state assigned as $(d_{5/2})^{-1}$, indicating a spherical-deformed shape coexistence.

[n]The $5/2^-[532]$ and $7/2^-[523]$ Nilsson states originate from the $h_{11/2}$ orbital and are expected to have a strong Coriolis coupling. This results in a very small moment-of-inertia parameter for the $5/2^-[532]$ band.

[o]Parameters calculated from the only other known levels, 5/2 (1292 keV) and 7/2 (1441 keV).

[p]The moment-of-inertia parameter evaluated from 3/2 (1818 keV) and 7/2 (1983) keV) levels.

[q]The lowest level of the unfavored sequence of the $h_{11/2}$ band $(9/2^-)$ was observed at energy 262.97 keV with $\log ft=6.67$.

[r]The 992 and 984 keV transitions to the ground-state band have large E0 components, so that Bunker and Reich (1971) suggest a $\{3/2^+[411]\otimes 0^+\}$ assignment.

TABLE IV. (*Continued*).

[s]Many other levels have been located by Devous and Sugihara (1977), but remain unassigned. Their calculations show that while bandhead states remain reasonably pure, higher members are strongly mixed. It is interesting that an $N=88$ nucleus exhibits many rotational bands. On the basis of these calculations a small deformation of $\beta=0.15$ has been assigned to this nucleus. Straume, Løvhøiden, and Burke (1976) assign $3/2^+$ to a 660-keV level, $5/2^+$ to levels at 534 and 725 keV, and $1/2^+$ to levels at 1170 and 1283 keV.

[t]Many levels above 944 keV observed by Boyno and Huizenga (1972) remain unassigned.

[u]Tippett and Burke (1972) and Boyno and Huizenga (1972) identify many other levels with the following tentative assignment: $7/2^+[404]$ and main component of fractionated $1/2^+[411]$ at 998 keV. Gasser *et al.* (1975) also offer the following tentative assignments: $3/2^-[541]$ at 1477.6 keV, $\{3/2^+[411]\otimes 0^+\}$ at 1149.9 keV, and $\{5/2^+[413]\otimes 0^+\}$ at 1349.7 keV.

[v]Two levels at 674 keV and 994 keV are considered to be unresolved doublets (Sugarbaker, 1977) consisting predominantly of $3/2^+$ levels, but also of the 1/2 member of two $K=1/2^+$ bands. The levels in these bands are 3/2 (674 keV), 5/2 (709 keV), and 7/2 (789 keV), and 3/2 (994 keV), 5/2 (1110 keV), 7/2 (1184 keV), and 9/2 (1371 keV). An admixture of γ vibration is probably present in these bands.

the state $K^\pi[Nn_z\Lambda]$ occurring in the chain of isotopes, or isotones, listed in the first row of the table. Vibrational excitations or their admixtures are indicated by the base-state configuration coupled to the type of phonon excitation. The Nilsson configuration for the particle states upward from the Fermi surface for the beta-stable species are listed first, followed by the hole states listed in order downward from the Fermi surface. It is to be remembered, however, that this is an approximate classification, since, particularly close to the Fermi surface, the distinction between the particle and the hole states may be blurred, while the two types may even switch character in regions well away from the stability line.

Each successive column then corresponds to the nuclide specified in the topmost row. Data entries are made at three subrows for each major row (delineated by horizontal solid lines) involving a specific Nilsson configuration. In the first subrow we list twice the spin ($2I$) in parentheses, *only* for those cases in which $I\neq K$, followed by the energy (in keV) for that particular Nilsson state. In the middle subrow is listed the moment-of-inertia parameter A (in keV) rounded off to the first decimal place and derived, using Eq. (3.16), from the first two rotational level energies, unless mentioned otherwise; this is followed by the decoupling parameter "a" for the $K=1/2$ bands rounded off to two decimal places and calculated using Eq. (3.16) from the first three rotational level energies (1/2, 3/2, and 5/2), unless otherwise noted. In the bottom subrow we list the log ft values for beta transitions feeding the level, that for β^- on the left and for β^+/EC on the right.

A subscript "iso" to the energy value denotes an isomer with an arbitrarily chosen limit of ($t_{1/2}\geq 1$ μsec). The logft value for the beta decay of an isomer is also denoted by a subscript "iso." The references for the experimental data on each nuclide are given at the bottom of the table, including the most recent Nuclear Data Sheets (abbreviated "NDS"), followed by the references on β-decay studies and reaction studies, in that order. The footnotes contain other information and comments of interest for each nuclide. Sometimes the signature quantum number $\alpha=+1/2$ and $-1/2$ has been used in the footnotes to denote rotational sequences $I=1/2$, 5/2, 9/2 . . . and $I=3/2$, 7/2, 11/2 . . . , respectively.

B. Three-quasiparticle states

At excitation energies above the energy gap 2Δ (~ 1 Mev in the rare-earth region), a coupled nucleon pair can break to form a three-quasiparticle (3qp) state by coupling with the unpaired nucleon in odd-A nuclei. Four kinds of 3qp states are possible. They are *nnn*, *ppp*, *nnp*, and *ppn*. Each 3qp multiplet has four possible bands with $K=|K_1\pm K_2\pm K_3|$, whose splitting provides a measure of the residual interaction. However, reliable data on 3qp multiplets are scarce.

Experimental data on 3qp states were presented by Bunker and Reich (1971) and, in the specific context of fast beta decays, by Meijer (1976) and Sood and Sheline (1989b). We present in Tables XXIV and XXV, respectively, the data on the odd-Z and the odd-N 3qp states in the rare-earth region. The data entries include the configuration assignment, excitation energy, moment-of-inertia parameter, and logft values. As in the other tables, the probable assignments are enclosed in parentheses. It may be noted that with the exception of the two (*ppp*)-type 3qp states observed for ^{177}Ta and ^{179}Ta, all the known 3qp states are of the (*ppn*)-type in the odd-Z and of the (*nnp*)-type in the odd-N nuclei of this region.

It is interesting to note that most of the 3qp states seen are clustered in $Z=70$ to 73 nuclei, with the maximum number seen in Hf($Z=72$) and Ta($Z=73$) isotopes. It is clear from the tables that no complete multiplet of 3qp states has been observed in any nucleus. It therefore remains an important experimental challenge to reliably identify 3qp multiplets in odd-A nuclei and, in particular, to observe examples of all four couplings of the same 3qp configuration.

We do not show some of the low-lying 3qp states listed by Meijer (1976) and others in our compilation. Evidence suggests that 3qp configurations are actually a *part* of the total wave function of these states, with other

TABLE V. Intrinsic states of $Z=67$ odd-A nuclei.

$_{67}$Ho	$A=155$[a]	157[b]	159[c]	161[d]	163[e]	165[f]	167[g]	169[h]
7/2$^-$[523][i]		0 9.2	0 10.8	0 11.0	0 11.1 4.84	0 10.8 6.2 4.7	0 11.1	0 10.8
1/2$^+$[411][j]			205.7$_{iso}$ 11.1 −0.8 6.04	211.1$^{k}_{iso}$ 11.3 −0.66 6.8	297.9$^{k}_{iso}$ 10.1 −0.67 9.04	429.4 12.3 −0.46 6.6$_{iso}$	(392.5) 6.7	(3) 359
7/2$^+$[404]	110.2[l]	66.9	165.9 12.7[m] 8.73	252.7 13.1	(439.9) 12.4 9.3	715.3 11.6 8.1	(974)	1079
5/2$^+$[402]	0	53.1	252.9 8.04	446.8	(710)	(1055.8) 12.1 6.9	(1403)	(1693)
1/2$^-$[541]		(482.3) 10.1 1.89	424.1 10.3 2.11 7.44	423.9 10.3 2.3 7.4	471.2 10.0 2.55	681.2 9.4 2.89		
9/2$^-$[514]		(11) (996)	(11) (1156)		(11) (1436)[n]	(1479.7) 10.2		
3/2$^+$[411]		(91.1) 11.9		298.7 14.9	360.4 16.0	361.7$_{iso}$ 11.6 6.5$_{iso}$	(259.3)$_{iso}$ 12.1 ≥ 6.5	254 12.0
5/2$^+$[413]		(549.1) 6.6	671.6 15.6 6.87	760.5 14.2	876 13.7 7.03	995.1 12.1 5.7	(7) (1165) 12.2	(7) 1179 10.9
5/2$^-$[532]		(391.3) 6.0	(624.4) 13.2 5.61	826.6 11.3 5.4	1113.6 10.9 5.46	(1416.4) 9.5	(7) (1464)	(7) 1366
1/2$^+$[420]					(1636)[o] 16.8 1.0	(1704) 11.5 −0.05[p]	(1858)	1786
11/2$^-$ ($h_{11/2}$)	142.0$^{g}_{iso}$ 13.5							
3/2$^-$ {7/2$^-$[523]$\otimes 2^+$}				592.7 11.3	560 11.6	515.5 10.3 5.2$_{iso}$	(569.7) 5.4	

TABLE V. (*Continued*).

$_{67}$Ho	$A=155$[a]	157[b]	159[c]	161[d]	163[e]	165[f]	167[g]	169[h]
$11/2^-$ $\{7/2^-[523]\otimes 2^+\}$		(688.5) 10.1						
$3/2^+$ $\{7/2^-[404]\otimes 2^+\}$ $+3/2^+[402]$								955
$1/2^+$ $\{5/2^-[402]\otimes 2^+\}$ $+1/2^+[400]$								1100
$1/2^+$ $\{3/2^+[411]\otimes 2^+\}$		1037.5 11.2 −0.13 ~7.4						
Other levels	u	v				r	s	t

[a]Lee (1987): NDS; Budzyak *et al.* (1980): decay; Hagemann *et al.* (1984): (^{18}O,$4n\gamma$); Foin *et al.* (1979): (^{14}N,$4n\gamma$); Devous and Sugihara (1978): (^{10}B,$5n\gamma$).

[b]Helmer (1988): NDS; Boutet *et al.* (1977): decay; Panar *et al.* (1977): (^{3}He,d), (α,t); Grosse *et al.* (1974): (^{11}B,$4n$); Hagemann *et al.* (1982, 1984): (^{15}N,$4n$); Simpson *et al.* (1985, 1986): (^{37}Cl,$4n$).

[c]Lee (1988): NDS; Boutet (1977), Geiger *et al.* (1971): decay; Grosse *et al.* (1974): (^{11}B,$4n\gamma$); Forsblom *et al.* (1975): ($\alpha,4n\gamma$); Spalek *et al.* (1977): ($\alpha,4n\gamma$), (^{3}He,$3n\gamma$); Panar *et al.* (1977): (^{3}He,d), (α,t); Hammarén and Burke (1982): (p,α).

[d]Helmer (1984): NDS; Geiger *et al.* (1971): decay (IT); Kaun *et al.* (1972), Wood and Brenner (1972), Harmatz and Handley (1972): decay; Grosse *et al.* (1974), Alonso *et al.* (1971): (^{11}B,$4n\gamma$); Funke, Kaun, Kemnitz, Sodan, and Winter (1971), Rensfelt *et al.* (1970): ($\alpha,2n\gamma$), ($d,2n$), (p,n); Panar *et al.* (1977): (^{3}He,d), (α,t); Burke *et al.* (1981): (t,α).

[e]Burrows (1989): NDS; Geiger and Graham (1967): decay (IT); Funke *et al.* (1972): decay, ($d,2n\gamma$), ($p,n\gamma$); Panar *et al.* (1977), Lewis *et al.* (1974): (^{3}He,d), (α,t); Goles *et al.* (1973): (p,t); Broad *et al.* (1976): (^{3}He,d); Burke *et al.* (1981): (t,α).

[f]Peker (1987): NDS; Mauron *et al.* (1972), Starner *et al.* (1974): decay; Seaman *et al.* (1967): Coul.; Alonso *et al.* (1971): (^{10}B,^{10}B$'\gamma$); Kuvaga *et al.* (1981): ($n,n'\gamma$); Lewis and Gray (1975): (d,^{3}He); Barnard *et al.* (1972): ($n,n'\gamma$), (n,n'); Wagner *et al.* (1975): (^{3}He,d), (α,t).

[g]Tuurnala *et al.* (1977): decay; Løvhøiden, Burke, *et al.* (1979): (t,α).

[h]Shirley (1982): NDS; Sugarbaker (1977): (d,^{3}He); Løvhøiden, Burke, *et al.* (1979): (t,α).

[i]Expected to have a mixed $h_{11/2}$ character due to Coriolis mixing. Alignment of the second, and probably the third, pair of $h_{11/2}$ quasiprotons is observed in ^{157}Ho by Simpson *et al.* (1985). These crossings show that significant proton pair correlations must remain for this configuration up to high spins ($\sim 40\hbar$). Hagemann *et al.* (1982) report a signature dependence in the transition rates and level energies of ^{157}Ho that disappears at the first bandcrossing. It is suggested that a large change in shape occurs at higher spins. However, these features are unexplained within the available models. Coriolis-mixing calculations for ^{161}Ho carried out by Rensfelt *et al.* (1970) require a reduction of Coriolis matrix elements, particularly those near the Fermi energy.

[j]The bands based on $1/2^+[411]$, $3/2^+[411]$, and $5/2^+[402]$ mix strongly by Coriolis coupling. Calculations by Funke, Kaun, Kemnitz, Sodan, and Winter (1971) and Hammarén and Burke (1982) for ^{161}Ho show the need of extra enhancement of the $\langle 1/2^+[411]|3/2^+[411]\rangle$ matrix element and the reduction of the $\langle 3/2^+[411]|5/2^+[402]\rangle$ matrix element to reproduce the band structure and the anomalous transfer strengths in stripping and pickup reactions.

[k]Panar *et al.* (1977) observe some interesting anomalies in the strengths of 3/2, $3/2^+[411]$ and 5/2, $1/2^+[411]$ states in ^{161}Ho as well as ^{163}Ho. Coriolis mixing could explain only part of the mixing effects. In particular, very large strength of the 3/2, $3/2^+[411]$ state in ^{163}Ho remains unexplained (Burke *et al.* (1981).

[l]Levels 9/2 and 11/2 lie at 344.9 and 582.8 keV, respectively.

[m]Value calculated from the 7/2 and 15/2 rotational level energies.

[n]Level energy taken as an average of values from (α,t) and (^{3}He,d).

TABLE V. (*Continued*).

[o]The 1733 keV level is interpreted as a doublet comprising 5/2 and 3/2 levels of this band. The decoupling parameter $a=+1.0$ gives rise to an interesting situation of decoupled bands. See text.

[p]Values calculated from $1/2^+$ (1704 keV), $5/2^+$ (1797 keV), and $7/2^+$ (1873 keV).

[q]Bandhead of $h_{11/2}$ decoupled band having signature $\alpha=-1/2$. The moment-of-inertia parameter is evaluated from 11/2 (142.0 keV) and 15/2 (518.8 keV) levels.

[r]Panar *et al.* (1977) tentatively assign the 1/2, 3/2 members of the $1/2^+$[411] band to a doublet at 273 keV with the 5/2 and 7/2 members at 356 and 374 keV, respectively. These authors also tentatively assign a level at 629 keV as a $K=1/2$ γ-vibrational state built on $5/2^+$[402]. Similarly, a 639-keV level is speculated to be due to a $3/2^+$[402] admixture in the $K=3/2$ γ vibration built on $7/2^+$[404].

[s]Hammarén and Burke (1982) observe two states with a clear $l=0$ distribution in the region where the $1/2^+$[420] band would be expected to appear, namely, at 1178 keV and 1201 keV excitation energies. They tentatively associate the higher one to the $1/2^+$[420] band. In addition, Panar *et al.* (1977) observe a $K=1/2$ γ-vibrational band based on the $5/2^+$[402] state at 875 keV. These vibrations would be expected to have a significant $1/2^+$[400] single-particle admixture, as the $1/2^+$[400] and $5/2^+$[402] orbitals are connected by a large E2 matrix element. Lee (1988) also suggests that a 580.7 keV level may be the $(K-2)$ vibrational state based on the $7/2^-$[523] ground state.

[t]Among other observed levels are a 1280-keV level tentatively assigned as the $11/2^-$ member of the $9/2^-$[514] band, and 1436-, 1529-, and 1545-keV levels tentatively assigned as the 1/2, 5/2, and 3/2 members of the $1/2^+$[420] band.

[u]Lewis *et al.* (1974) report the observation of unassigned levels at 1128, 1350, and 1371 keV with l transfers 2, 0, and 3, respectively.

[v]Wagner *et al.* (1975) propose a $1/2[K-2]$ band at 1616 keV based on the $5/2^+$[402] state in the stripping reaction. In the (t,α) reaction, there are two strongly populated hole states at 1486 and 1676 keV. Possible assignments for these states are the 7/2 and 11/2 members of the $5/2^-$[523] band. Kuvaga *et al.* (1981) also observe levels at 1236, 1338, 1534, and 1547 keV, which remain unassigned.

TABLE VI. Intrinsic states of $Z=69$ odd-A nuclei.

$_{69}$Tm	$A=159$[a]	161[b]	163[c]	165[d]	167[e]	169[f]	171[g]	173[h]	175[i]
$1/2^+$[411]		7.3[j] 17.0 −0.69	0 15.3 −0.71 5.6	0 13.7 −0.72	0[k] 12.4 −0.72	0 12.4 −0.77 6.44	0 12.0 −0.86 8.53	0 12.0 −0.93	0[l] 12.6 −0.99
$7/2^+$[404]	52.9 21.5	0 18.0	23.3[m] 15.7 >9.6	80.4^{n}_{iso} 14.5	179.6^{n}_{iso} 13.0	316.1 13.0 8.5	635.6 ~9.7		
$1/2^-$[541]		(367.2)[o]	217.1[m,p] 11.5 2.2 7.1	(158.2) 11.5 2.63	171.7 9.5 3.16	(341.7) 9.2 3.82	(5) 750.3 7.1 4.77		
$5/2^+$[402]	0	18.9 20.0	136.7 16.6	315.5 14.9 <7.1	557.9 14.3 8.4	(781.6)	913.1 12.2		(1423)
$9/2^-$[514]				(11) 830.9	(929.8)	(11) (1152)	(11) (1307.1)	1212.8 4.3	

TABLE VI. (*Continued*).

$_{69}$Tm	$A=159$[a]	161[b]	163[c]	165[d]	167[e]	169[f]	171[g]	173[h]	175[i]
{7/2$^-$[523], $h_{11/2}$}[q]	166.3[r]	78.1 7.9	86.9[m] 9.7	160.5_{iso} 10.2 4.8	292.9 10.1 4.6	379.2 10.4 7.0	425.1_{iso} 10.6 6.38	317.7_{iso} 10.5 5.7	439 10.3
3/2$^+$[411]		(337.4) 19.1	366.4 17.4 6.9	491.2 23.7	471.3[s] 10.2 7.8	570.8[t] 12.4	676.0[u] 12.3 6.66		608 12.2
5/2$^-$[532]		(709.7)			1527.4 6.1				
5/2$^+$[413]					1580.8 6.2				1706 14.9
3/2$^-$[532] +{1/2$^-$[541]⊗2$^-$}					852.9 5.9				
11/2$^+$ {7/2$^+$[404]⊗2$^+$}					944.9 12.0				
Other levels			v						w

[a]Lee (1988): NDS; Holzmann *et al.* (1983, 1985): (^{22}Ne,4n); Larabee and Waddington (1981): (^{14}N,3n); Larabee *et al.* (1984): (^{14}N,3n), (^{22}Ne,4n); André *et al.* (1985): (^{14}N,5n).
[b]Adam *et al.* (1981): decay; Foin *et al.* (1984): (^{14}N,5$n\gamma$), (α,8$n\gamma$).
[c]Burrows (1989): NDS; Adam, Gromov, *et al.* (1975): decay; Foin *et al.* (1977): (^{3}He,5$n\gamma$), (α,6$n\gamma$).
[d]Peker (1987): NDS; Tamura *et al.* (1973): decay; Gizon *et al.* (1972), Foin *et al.* (1975): (α,4$n\gamma$); Cheung *et al.* (1974): (^{3}He,d), (α,t).
[e]Funke, Kaun, Kemnitz, Sodan, Winter, *et al.* (1971): decay; Olbrich *et al.* (1980), Ionescu *et al.* (1981): (α,2$n\gamma$); Svensson *et al.* (1976): (p,2$n\gamma$), (p,$n\gamma$); Cheung *et al.* (1974): (^{3}He,d), (α,t).
[f]Shirley (1982): NDS; Verma *et al.* (1978), Balaheav and Dzhelepov (1972): decay; Cheung *et al.* (1974): (^{3}He,d), (α,t); Barneoud *et al.* (1974): (p,2$n\gamma$), (d,3$n\gamma$).
[g]Shirley (1984): NDS; Graham *et al.* (1972), Gopinathan and Patel (1975), Badica *et al.* (1978): decay; Cheung *et al.* (1974): (^{3}He,d), (α,t); Drissi *et al.* (1988): (^{7}Li,2$n\alpha$).
[h]Shirley (1988): NDS; Pursiheimo *et al.* (1972): decay; Tarara *et al.* (1978): (p,α).
[i]Løvhøiden, Andersen, *et al.* (1979): (t,α).
[j]Only $\alpha=-1/2$ sequence is populated in (HI,xn) reactions.
[k]Olbrich *et al.* (1980) report an energy discrepancy of ≤ 200 eV for the 5/2$^+$ level between the results of Funke, Kaun, Kemnitz, Sodan, Winter, *et al.* (1971) and Svensson *et al.* (1976). This is probably due to the doublet character of the 116.69 keV transition. Olbrich *et al.* (1980) give an intermediate value. Since the level plays a key role in the whole scheme, the discrepancy affects many other level energies.
[l]Values calculated from the 1/2, 5/2, and 9/2 levels at 0, 126, and 353 keV, respectively. The 3/2 and 7/2 levels are degenerate with the 1/2 and 5/2 levels, respectively.
[m]The 7/2$^+$[404], 7/2$^-$[523], and 1/2$^-$[541] bands are known up to high spins. The former two exhibit a backbending behavior similar to neighboring even-even nuclei, while the 1/2$^-$[541] band does not backbend.
[n]The 7/2$^+$[404] band in ^{165}Tm exhibits a large odd-even staggering at high spins, which is very unusual for such a band. A $\Delta K=3$ coupling with the 1/2$^+$[411] band is suggested for $I=15/2$, 19/2, and 23/2 levels in the two bands, which lie very close in energy (Foin *et al.*, 1975). Interband E2 and E1 transitions seem to support such a mixing. Similar observations have been made by Olbrich *et al.* (1980) in ^{167}Tm.
[o]Only $\alpha=+1/2$ sequence is known. The 5/2 and 9/2 levels lie at 376.6 and 516.5 keV, respectively.

TABLE VI. (*Continued*).

[p]On the basis of Coriolis-mixing calculations for the $1/2^-[541]$ band, Foin *et al.* (1977) suggest the identification of the $3/2^-[532]$ configuration bandhead with an unassigned level at 1130.6 keV feeding the 1/2 and 3/2 levels of the $1/2^-[541]$ band.

[q]Strong Coriolis mixing with other $h_{11/2}$ states present.

[r]Holzmann *et al.* (1983, 1985) establish the favored ($\pi=-$, $\alpha=-1/2$) and unfavored ($\pi=-$, $\alpha=+1/2$) $h_{11/2}$ proton bands up to $59/2^-$ ($\hbar\omega$=0.454 MeV) and $61/2^-$ ($\hbar\omega$=0.48 MeV), respectively. This is well above the frequency region in which a second backbending is known to occur in the neighboring even-even nuclei. The excitation energy of the $7/2^-$ level with respect to the $5/2^+$ ground state could not be known. From the systematics of the odd-thulium isotopes (Adam *et al.*, 1981), it can be estimated to be $E(7/2^-)\cong 80$ keV. On the other hand, the André *et al.* (1985) show that the intense 166.3-keV γ line is not the $11/2^-\rightarrow 7/2^-$ transition of the $7/2^-[523]$ band but, on the contrary, an interband isomeric transition, thus placing the state at 166.3 keV.

[s]The $3/2^+[411]$ bandhead was first observed by Funke, Kaun, Kemnitz, Sodan, Winter, *et al.* (1971). They also found two possible $I=5/2$ levels at 522.2 and 557.8 keV and suggested the lower one was the first excited state in the $3/2^+[411]$ band. However, Cheung *et al.* (1974) concluded that this level is most likely the $5/2^+[402]$ bandhead, and suggested that the 558-keV level is the 5/2 level in the $3/2^+[411]$ band. These latter assignments were supported by the results of Svensson *et al.* (1976). Olbrich *et al.* (1980), however, confirm the observations of Funke *et al.*

[t]Calculations of Soloviev *et al.* (1967) suggest a 12% γ-vibrational admixture of the configuration $\{1/2^+[411]\otimes 2^+\}$.

[u]A large logft value for the $1u$ transition and the similarity of this state to the $3/2^+$ state seen in ^{169}Tm suggest a vibrational admixture of $\{1/2^+[411]\otimes 2^+\}$ here (Bunker and Reich, 1971).

[v]Adam, Gromov, *et al.* (1975) observe strongly populated levels at 947.3 keV and 1833.5 keV possibly having $I^\pi=5/2^-$. They suggest an assignment of $5/2^-[532]$ for the 947-keV level and a large three-quasiparticle admixture of the type $5/2^-$ $\{7/2^-[523]p, 3/2^-[521]_n, 5/2^-[523]_n\}$ for the 1833-keV level.

[w]It is suggested by Løvhøiden, Andersen, *et al.* (1979) that the 1916-keV and the 2095-keV levels are 7/2 and 11/2 members, respectively, of the $5/2^-[532]$ band. Some strongly populated levels yet unassigned are the 1985- $(5/2^+)$, 2013- and 2056-keV levels. Levels at 1146 keV $(7/2^+, 3/2^+)$, 1365 keV $(7/2^+)$, 1212 keV $(7/2^-, 5/2^+)$, and 1495 keV $(7/2^-, 5/2^+)$ also remain unassigned. The 1146- and the 1365-keV levels may be the fragments of the $7/2^+[404]$ state.

TABLE VII. Intrinsic states of $Z=71$ odd-A nuclei.

$_{71}$Lu	$A=165$[a]	167[b]	169[c]	171[d]	173[e]	175[f]	177[g]
$7/2^+[404]$	(0)[h]	0 15.5 >5.3	0 13.7 >5.6	0 13.6	0 13.0	0 12.6 6.3	0 13.5 6.5
$1/2^-[541]$			29.0_{iso} 9.9 3.30	71.3_{iso} 9.2 3.90	(5) 123.7^{i}_{iso} 8.5 4.27 7.5	(5) 353.6^{j}_{iso} 7.8 5.11 9.2	(5) 761.6[k] 7.1 6.36
$5/2^+[402]$				295.6[l] 14.2	357.0 13.4 9.4	343.5 12.8 6.7	457.9 13.5
$9/2^-[514]$		331.8 9.3	(439.1) 9.7	469.2 11.3	(449.0) 11.9	396.3 12.1 4.7	150.4 12.6 6.7
$1/2^+[660]$				(13) (1569)	(721.5) 10.0		

TABLE VII. (*Continued*).

$_{71}$Lu	$A=165$[a]	167[b]	169[c]	171[d]	173[e]	175[f]	177[g]
$3/2^-[532]$				(5) (968) 17.8[m]	889.2 13.7 8.7	(999.0) 12.9	(1322.1)
$1/2^-[530]$				(3) (1110)	(3) 1162.5[n] 7.0		
$3/2^+[402]$					(1359.3)[o] 8.8		
$1/2^+[400]$					(1409) 8.4		
$1/2^+[411]$			(97.4) 13.9 −0.61	208.3[l] 13.4 −0.69	425.3 13.3 −0.76 6.6	(626.7) 13.5 −0.85	569.6_{iso} 14.2 −0.91
$7/2^-[523]$	(180.0)[h] 4.7	315.2[p] <4.9	(492.9) 4.4	662.2 14.0	(734.7)		
$3/2^+[411]$					975.1 7.7	(1150.8) 13.6	
$1/2^+$ $\{1/2^-[541]\otimes 1^-\}$					981.7 7.8		
$1/2^+$ $\{1/2^+[411]\otimes 0^+\}$					1246.3 8.3		
$3/2^-$ $\{1/2^-[541]\otimes 2^+\}$					1333.9 7.1		

TABLE VII. (*Continued*).

$_{71}$Lu	$A=165$[a]	167[b]	169[c]	171[d]	173[e]	175[f]	177[g]
$11/2^+$ $\{7/2^+[404]\otimes 2^+\}$							1305.6[q]
Other levels		r	s		t	u	

[a]Hild *et al.* (1989): decay.

[b]Meijer *et al.* (1973): decay; Barneoud and Foin (1977): (^{3}He,$5n\gamma$), (α,$6n\gamma$).

[c]Shirley (1982): NDS; Meijer *et al.* (1973), Chu and Reednick (1970): decay; Foin *et al.* (1973): (α,$4n\gamma$), (p,$3n\gamma$).

[d]Shirley (1984): NDS; Gnatovich *et al.* (1974): decay; Hjørth *et al.* (1972), Barneoud *et al.* (1972), Kemnitz *et al.* (1973): (α,$2n\gamma$); Kemnitz *et al.* (1971): (α,$2n\gamma$), (d,$2n\gamma$); Gregory *et al.* (1973): (^{3}He,d), (α,t) (α,$2n\gamma$).

[e]Shirley (1988): NDS; Gnatovich *et al.* (1972), Funk *et al.* (1974), Brenner *et al.* (1975): decay; O'Neil *et al.* (1971): (^{3}He,d), (α,t); Kemnitz *et al.* (1973): (d,$2n\gamma$), (p,$n\gamma$); Schilling *et al.* (1976): (p,$n\gamma$).

[f]Johansen *et al.* (1969), Reierson *et al.* (1970), Grigorev and Sergeenkov (1971): decay; Foin *et al.* (1974), Winter, Andrejtscheff, *et al.* (1974): (p,$2n\gamma$); O'Neil *et al.* (1971): (^{3}He,d), (α,t); Minor *et al.* (1971): (d,t); Skensved *et al.* (1981): Coul.

[g]Brown *et al.* (1970), Morii (1975): decay; Manfrass *et al.* (1971), Manfrass and Andrejtscheff (1972), Geinoz *et al.* (1975): (n,γ); Minor *et al.* (1971): (d,p), (n,γ); O'Neil *et al.* (1971): (^{3}He,d), (^{3}He,t).

[h]Assignments are based on systematics and a low log ft value of 4.7 for the feeding of the 180-keV state, provided the feeding to the ground state is neglected. Assuming that $5/2^-[523]$ is the ground state of ^{165}Hf (from the systematics), the au β transition to the 180.0-keV state gives it an assignment of $7/2^-[523]$. This is the only type of au transition seen in the mass range $155 < A < 171$. Two assignments are possible for the ground state of ^{165}Lu, namely, a 1/2 value from the magnetic-resonance data (Ekström *et al.* 1974) and a $7/2^+$ value from the decay data (Rastikerder *et al.* 1981). The 1/2 level seems to lie higher than the 7/2 level (Peker, 1987). We have therefore chosen $7/2^+[404]$ as the ground state.

[i]The 1/2 level lies at 128.3 keV. Strong Coriolis mixing of this state with the $3/2^-[532]$ state is expected.

[j]The 1/2 level lies at 371.0 keV.

[k]The 1/2 level of this band lies at 795.2 keV.

[l]Kemnitz *et al.* (1973) observe transitions between some states of the $1/2^+[411]$ and $5/2^+[402]$ bands in ^{171}Lu, indicating a strong $\Delta K=2$ mixing. Similarly, a $\Delta K=4$ mixing between states of the $1/2^-[541]$ and $9/2^-[514]$ bands is indicated by interband transitions. Kemnitz *et al.* (1973) could explain these effects by considering only the interaction between $\Delta K=1$ states.

[m]Calculated from the transition between 7/2 (1182 keV) and 5/2 (968 keV) levels.

[n]The 1/2 level lies at 1192.7 keV.

[o]Brenner *et al.* (1975) propose a $\Delta N=2$ mixing between the $3/2^+[402]$ and $3/2^+[651]$ orbitals.

[p]More than 65% of the total decay proceeds directly to this state. No other band members are known. Barneoud and Foin (1977), however, did not find any evidence of the $7/2^-[523]$ state.

[q]Soloviev and Vogel (1967) have calculated the properties of the γ vibrations in ^{177}Lu and have predicted the 11/2, $\{7/2^+[404]\otimes 2^+\}$ γ vibration to lie at ~ 1300 keV. Minor *et al.* (1971) argue that since there is no bound $\Omega^\pi=11/2^+$ proton orbital in this energy region that can mix into this state, the $(K+2)=11/2^+$ γ vibration is expected to be made up almost entirely of three-quasiparticle components that can couple to spin and parity $11/2^+$. The $K^\pi=11/2^+$ $\{7/2^+[404]_p, 7/2^-[514]_n, 3/2^-[512]_n\}$ three-quasiparticle configuration is expected to be populated in the (d,p) reaction. However, the state observed at 1305.6 keV has $\sim 50\%$ of the single-particle strength of that predicted for the pure $11/2^+$ three-quasiparticle configuration.

[r]Additional bands based on $1/2^+[411]$ and $1/2^-[541]$ configurations have been observed up to high spins by Barneoud and Foin (1977). However, their absolute locations could not be determined. Another tentatively assigned band is $5/2^+[402]$, observed up to $I=15/2$, whose location also remains unknown.

[s]An additional $5/2^+[402]$ rotational band is identified by Foin *et al.* (1973); however, its location with respect to the ground state is unknown. The absolute locations of $1/2^-[541]$ and $1/2^+[411]$ band members (except the bandhead) are also unknown.

[t]Funk *et al.* (1974) observe a $3/2^+$ vibrational state arising from the configuration $\{1/2^-[541]\otimes 1^-\}$ and a $1/2^-$ state from the $\{1/2^-[541]\otimes 0^+\}$ configuration at 1097.4 and 1129.5 keV, respectively. The highly tentative state 1578 keV might be considered as $1/2^+$ $\{1/2^-[541]\otimes 0^-\}$.

[u]Among other levels are 1315-keV and 1332-keV levels, tentatively observed and assigned as the 3/2 and 1/2 members of the $1/2^-[530]$ band by Winter, Andrejtscheff, *et al.* (1974) and O'Neil *et al.* (1971).

TABLE VIII. Intrinsic states of $Z=73$ odd-A nuclei.

$_{73}$Ta	$A=171$[a]	173[b]	175[c]	177[d]	179[e]	181[f]	183[g]	185[h]
7/2$^+$[404]		35.0 14.5	0 14.4	0 14.6	0 14.9	0 15.1 7.1	0 15.9	0 18.1
5/2$^+$[402]			(36.4) 15.2	70.6 14.5	238.6 15.1 7.7	482.2	459.1 16.2 6.79	
1/2$^-$[541][i]	(5) 0 12.8 4.32	(5) 0 12.9 4.76	(5) 51.4[j] 8.2 5.06	(5) 186.1^{j}_{iso} 12.1 5.54 6.2	(5) 628.1 12.9 6.06			
9/2$^-$[514]		165.2 12.7	(131.6) 13.2	73.6 13.3	30.7_{iso} 13.7 4.6	6.2_{iso} 13.8 6.6	73.1	(~163) 15.7
3/2$^-$[532]				(690.2) 7.5				
1/2$^-$[530]				(1094.0) 7.3				
1/2$^+$[411]			(339.2)	487.6 15.9 −0.79 6.3	520.3 15.8 −0.85 6.6	615.2_{iso} 7.2		(~409)
3/2$^+$[411]				865.0 16.6 7.8				
7/2$^-$[523]								890 10.0
5/2$^-$ {9/2$^-$[514]⊗2$^+$}							856.8[k] 5.88	
Other levels	l	m			n	o		p

[a]Bacelar, Chapman, *et al.* (1985): (^{16}O,4$n\gamma$), (^{51}V,4$n\gamma$).
[b]Shirley (1988): NDS; André, Barneoud, *et al.* (1977): (^{12}C,4$n\gamma$), (α,6$n\gamma$); Bacelar, Chapman, *et al.* (1985): (^{18}O,4$n\gamma$).
[c]Table of Isotopes (Lederer and Shirley, 1978): decay; Foin *et al.* (1972): (α,4$n\gamma$).
[d]Ader and Perrin (1972): decay; Schilling *et al.* (1973), Skanberg *et al.* (1970), Barneoud *et al.* (1970), Barneoud *et al.* (1975), Hübel *et al.* (1971): (α,2$n\gamma$).

TABLE VIII. (*Continued*).

[e]Browne (1988): NDS; Konijn *et al.* (1969): decay; Manfrass *et al.* (1974): $(d,2n\gamma)$, $(p,n\gamma)$; Warde *et al.* (1982): (p,t); Barneoud *et al.* (1982): $(^7\mathrm{Li},4n\gamma)$.
[f]Firestone (1984): NDS; Avignone *et al.* (1971), Indira *et al.* (1979): decay; Rogers *et al.* (1970): $(n,n'\gamma)$; Forster *et al.* (1984): (n,γ); Inamura *et al.* (1976): Coul.
[g]Firestone (1987): NDS; McIsaac *et al.* (1969): decay; Van Assche *et al.* (1971): (n,γ).
[h]Ellis-Akovali (1981c): NDS; Løvhøiden *et al.* (1980): (t,α).
[i]Only $\alpha=+1/2$ sequence known except for a 15/2 level in ^{173}Ta and a 3/2 level in ^{175}Ta. Parameters are therefore evaluated by using 5/2, 9/2, and 13/2 level energies.
[j]The 1/2 level of this band lies at 216.6 keV in ^{177}Ta and at 68.7 keV in ^{175}Ta.
[k]A small admixture of the three-quasiparticle component $\{9/2^-[514]_p, 3/2^-[512]_n, 7/2^-[514]_n\}$ suggested by the calculations of Bes and Cho (1966).
[l]Additional bands based on the configurations $9/2^-[514]$, $5/2^+[402]$, and $7/2^+[404]$ have been identified up to high spins by Bacelar, Chapman, *et al.* (1985). The bandhead energies of these configurations are not known; however, they are believed to lie within 200 keV of the ground state. In addition, a band associated with the highly aligned $1/2^+[660]$ proton configuration is observed to cross the $5/2^+[402]$ band at $I^\pi=33/2^+$, becoming an yrast band at spins greater than $57/2^+$.
[m]André, Barneoud, *et al.* (1977) and Bacelar, Chapman, *et al.* (1985) observe the $5/2^+[402]$ band up to spin $27/2^+$, but the relative position of its bandhead with respect to the ground band is not known.
[n]At least five $7/2^+$ levels are reportedly observed by Warde *et al.* (1982) in the $l=0$ transfer (p,t) reaction, lying at 1298, 1475, 1527, 1739, and 1958 keV.
[o]Another 7/2 band, probably built on the $7/2^-[523]$ state, has been observed by Forster *et al.* (1984), but the bandhead energy is not known. It has a moment-of-inertia parameter of 14.86 keV. It is estimated to lie about 600–1400 keV above the $9/2^-[514]$ band.
[p]A level at 811 keV with spin $3/2^+$ may be either the $3/2^+[402]$ bandhead or the $I=3/2$ γ vibration based on the ground state. Another level at 1475 keV ($5/2^+$) may belong to a $3/2^+[411]$ configuration.

TABLE IX. Intrinsic states of $Z=75$ odd-A nuclei.

$_{75}$Re	$A=177$[a]	179[b]	181[c]	183[d]	185[e]	187[f]	189[g]	191[h]
$5/2^+[402]$	$(84.7)_{iso}$ 17.6	0 17.7	0 16.9	0 16.3	0 17.9 7.51	0 19.2 7.83	0 20.9	(97)
$1/2^-[541]$[i]	(5) 0 13.4 5.11	(5) 65.4^{j}_{iso} 13.9 5.93	(5) 356.8[k] 15.3 6.89 6.8_{iso}	(5) 598.8[l] 15.1 7.33	(5) (917)[m]	(9) (1200)[n]		
$1/2^+[400]$ $+\{5/2^+[402]\otimes 2^+\}$				(878.9) 17.0 +0.40 8.02_{iso}	(646.1) 17.0 0.40 7.3	511.7 18.7 0.38 >10.1		
$3/2^+[402]$				1034.9 7.60	(931.1) 16.4 8.55	(772.9) 21.3 7.33		
$5/2^+[642]$				(1040.7) 8.36				

TABLE IX. (*Continued*).

$_{75}$Re	$A=177^{a}$	179^{b}	181^{c}	183^{d}	185^{e}	187^{f}	189^{g}	191^{h}
$3/2^-[532]$			(867.0) $\geq 7.5_{iso}$	(1066.1)				
$11/2^-[505]$				1304.2 8.38		(1210)		
$1/2^+[660]$				1422		(1948)		
$3/2^+[651]$				(1470)		(1950)		
$9/2^-[514]$			(263.0) 17.4 $\geq 8.3_{iso}$	496.2 13.3 6.62	(368.2) 16.2	206.2 16.7	(125) 16.2	(145)
$7/2^+[404]$				851.4 16.8 7.57		(771)		(799)
$1/2^+[411]$	495.8	594	826.8 6.7_{iso}	1101.9 6.45_{iso}	880.5 7.16	(3) 618.3[o] 18.7 −1.12 7.59	(3) (260)	$(0)^{p}$
$3/2^+[411]$			1060.4 7.2_{iso}	(1353.8) 8.0		864.5 20.9 7.86		
$5/2^-[532]$ $+\{9/2^-[514]\otimes 2^+\}$						(685.7) 6.45		
$7/2^-[523]$								(11) (1229)
$1/2^-$ $\{1/2^-[541]\otimes 0^+\}$				(1414.7)				
$9/2^+$ $\{5/2^+[402]\otimes 2^+\}$					(966)	(840)		
Other levels	q	r	s		t	u	v	

TABLE IX. (*Continued*).

[a]Berlovich *et al.* (1976): decay; Leigh *et al.* (1972), Yang *et al.* (1983): (^{12}C,$4n\gamma$).
[b]Browne (1988): NDS; Berlovich *et al.* (1976): decay; Leigh *et al.* (1972): (^{11}B,$4n\gamma$).
[c]Firestone (1984): NDS; Akhmadzhanov *et al.* (1971): decay; Neskakis *et al.* (1976), Singh *et al.* (1974): ($\alpha,4n\gamma$).
[d]Firestone (1987): NDS; Brenner *et al.* (1983): decay; Lu and Alford (1971): (^{3}He,d), (α,t); Singh *et al.* (1974): ($\alpha,2n\gamma$).
[e]Ellis-Akovali (1981c): NDS; Behar *et al.* (1972), Plazner *et al.* (1970): decay; Lu and Alford (1971): (^{3}He,d), (α,t); Metzger (1967): (γ,γ'); Bisgård and Veje (1967): (d,d'); Evans *et al.* (1971): ($d,3n\gamma$); Smith *et al.* (1968): (n,n').
[f]Ellis-Akovali (1982): NDS; Brenner and Meyer (1976), Yamada *et al.* (1979), Singh *et al.* (1983): decay; Lu and Alford (1971): (^{3}He,d), (α,t); Langhoff (1967): (γ,γ'); Hirning and Burke (1976): (t,α); Hirning *et al.* (1977): (t,α); Bisgård and Veje (1967): (d,d').
[g]Firestone (1981): NDS; Kuaranen and Ihochi (1965): decay; Hirning and Burke (1976): (t,α); Hirning *et al.* (1977): (t,α).
[h]Browne (1989): NDS; Hirning and Burke (1976): (t,α); Hirning *et al.* (1977): (t,α).
[i]Mostly the levels of the $\alpha=+1/2$ sequence are observed. Parameters are evaluated by using 5/2, 9/2, and 13/2 level energies.
[j]The 1/2 level lies at 118.5 keV. The position of the 9/2 level (123 keV) has been estimated from Coriolis-mixing calculations and used in calculating the parameters.
[k]The 1/2 level lies at 432.5 keV.
[l]The 1/2 level lies at 700.64 keV.
[m]The 1/2 level lies at 1045 keV. Highly perturbed band. The usual calculation of rotational parameters yields negative values.
[n]The only other level assigned is 5/2 at 1233 keV.
[o]Highly perturbed band. The 1/2 level lies at 625.24 keV.
[p]Probable doublet comprising $I=1/2$ and 3/2 members.
[q]Leigh *et al.* (1972) and Yang *et al.* (1983) observe a band with possible Nilsson configuration $9/2^-[514]$, but the relative position of the 9/2, $9/2^-[514]$, and 5/2, $1/2^-[541]$ states is not known. The moment-of-inertia parameter is 14.89 keV.
[r]A rotational band having $\hbar^2/2\mathfrak{I}=15.05$ keV is assigned as based on the $9/2^-[514]$ state (Leigh *et al.*, 1972). However, its relative separation with respect to other known states is unknown.
[s]Akhmadzhanov *et al.* (1971) suggest the assignments of $3/2^+[402]$, $\{5/2^+[402]\otimes 2^+\}$, and $1/2^-[530]$ bandheads to levels at 788, 932, and 1108 keV, respectively.
[t]Among other levels known between 0.8 MeV and 1.7 MeV, three levels at 1303 keV, 1651 keV, and 1700 keV were tentatively assigned as $11/2^-$, $11/2^-[505]$; $3/2^+$, $3/2^+[651]$; and $1/2^+$, $1/2^+[660]$ by Lu and Alford (1971).
[u]Many levels lying between 0.8 MeV and 2 MeV are known and remain unassigned. Tentative assignments have been proposed for levels at 1230.5 and 1790 keV as the $5/2^-$ $1/2^-[541]$ state and the $11/2^-$, $7/2^-[523]$ state on the basis of (α,t), (^{3}He,d), and (t,α) data.
[v]A level at 697 keV has been tentatively interpreted as $7/2^+[404]$ by Hirning *et al.* (1977). Another strongly populated level at 1223 keV is given a tentative assignment of $I^\pi=5/2^+$. One more strongly populated level is observed at 1423 keV ($11/2^-$) and is tentatively assigned to the $7/2^-[523]$ band.

TABLE X. Intrinsic states of $Z=77$ odd-A nuclei.

$_{77}$Ir	$A=183^{a,g}$	185^{b}	197^{c}	189^{d}	191^{e}	193^{f}
$3/2^{+}[402]^{h}$		229.6 21.2	0 22.0	0 22.8 6.9	0 25.9 7.8	0 27.8 7.5
$1/2^{+}[400]^{h}$ $+\{3/2^{+}[402]\otimes 2^{+}\}$		332.8 28.1 0.02	106.4 26.1 0.06	94.3 27.8 −0.01 7.6	(82.4) 33.3 −0.03 7.23	73.0 36.0 −.009 7.8
$11/2^{-}[505]$ $(h_{11/2})$		646.8	433.8	372.2_{iso} 28.1	171.4_{iso} 5.3	80.2_{iso}
$1/2^{-}[530]$					(3) (1450)	
$1/2^{-}[541]^{i}$	(5) 0 19.0 7.57	(5) 0 11.8 7.75	(9) 186.1_{iso}			
$1/2^{+}[411]$				(3) (539)		(3) 460.5^{j} 7.5
$5/2^{+}[402]$ $+\{1/2^{+}[400]\otimes 2^{+}\}$	307 15.0				(588.0) 8.59	(970.0)
$7/2^{+}[404]$ $+\{3/2^{+}[402]\otimes 2^{+}\}$					(686.3) 28.9	(621) 30.1
$9/2^{-}$ $(h_{9/2})$				(563.4)		
Other levels				k	l	m

[a]Firestone (1987): NDS; Visvanathan *et al.* (1979): decay; André, Genevey-Rivier *et al.* (1977): $(\alpha,6n\gamma)$; Janzen *et al.* (1988): $(^{19}F,4n\gamma)$.

[b]Schuck *et al.* (1979): decay; André *et al.* (1979): $(\alpha,4n\gamma)$, $(\alpha,6n\gamma)$; Eder *et al.* (1986): *I*.

[c]Ellis-Akovali (1982): NDS; Sebille-Schück *et al.* (1973): decay; André *et al.* (1975): $(\alpha,2n\gamma)$; Kemnitz *et al.* (1975): $(\alpha,2n\gamma)$, $(\alpha,4n\gamma)$.

[d]Firestone (1981): NDS; Hedin and Bäcklin (1972): decay; André *et al.* (1975), Kemnitz *et al.* (1975): $(\alpha,2n\gamma)$; Løvhøiden *et al.* (1978), Struble *et al.* (1978): (p,t).

[e]Browne (1989): NDS; Bäcklin *et al.* (1970), Mälmskog, Berg, *et al.* (1970), Mälmskog *et al.* (1971): decay; Price and Johns (1971): decay, Coul.; Norgaard *et al.* (1971): (d,d'); Price *et al.* (1971): $(^{3}He,d)$, (α,t); Lukasiak *et al.* (1979): $(p,2n\gamma)$, $(d,3n\gamma)$; Struble *et al.* (1978): (p,t); McGowan *et al.* (1986): Coul.

[f]Shirley (1981): NDS; Bäcklin *et al.* (1970), Berg *et al.* (1970): decay; Price and Johns (1972): decay, Coul.; McGowan *et al.* (1987): Coul.; Norgaard *et al.* (1971): (d,d'); Price *et al.* (1971): $(^{3}He,d)$, (α,t); Yamazaki *et al.* (1978): (t,α).

[g]If the ground state of ^{183}Ir is assigned $I^{\pi}=5/2^{-}$ belonging to the 1/2[541] band (Janzen *et al.* 1988), we obtain $A=19.03$ keV and $a=7.57$ from the 5/2, 9/2, and 13/2 level energies.

[h]The $1/2^{+}$[400] and $3/2^{+}$[402] bands Coriolis mix with each other.

[i]Only $\alpha=+1/2$ sequence observed. The 1/2 level for ^{185}Ir probably lies at 135.3 keV. Parameters calculated from higher spin members (5/2 or 9/2, 13/2 and/or 17/2).

[j]The 1/2 level probably lies at 557.3 keV.

[k]Many other levels are reportedly observed by different workers, and there is no agreement on the assignments made. In particular, Hedin and Bäcklin (1972) assign $1/2^{-}$[541] and $3/2^{-}$[532] to levels at 540 and 828 keV, respectively. Struble *et al.* (1978) tentatively assign $\{5/2^{+}[402]+1/2^{+}[400]\otimes 2^{+}\}$, $1/2^{+}$[411], and $\{7/2^{+}[404]+3/2^{+}[402]\otimes 2^{+}\}$ to levels at 644, 719, and 748 keV.

[l]A doublet at 882 keV has been interpreted by Price *et al.* (1971) as the $9/2^{-}$, $1/2^{-}$[541] state and the $13/2^{+}$, $1/2^{+}$[660] state. Also, Norgaard *et al.* (1971) observed many unassigned levels between 0.5 MeV and 1.5 MeV.

[m]Price *et al.* (1971) indicate the presence of levels at 621, 1133, 1163, and 1760 keV with the tentative assignments $\{7/2^{+}[404]\otimes 2^{+}\}$, (5/2, $1/2^{-}$[541]), (13/2, $1/2^{+}$[660]), and (3/2, $1/2^{-}$[530]), respectively. Yamazaki *et al.* (1978) also support the assignments.

TABLE XI. Intrinsic states of $N=89$ odd-A nuclei.

$N=89$	^{151}Sm[a,e]	^{153}Gd[b]	^{155}Dy[c,f]	^{157}Er[d]
$3/2^-[521]$	104.9 12.7 8.3	0 8.3 8.5	0 7.9 6.17	(0)[g]
$5/2^-[523]$	0 9.4 > 8.0	109.7 8.05	136.3 6.93	
$5/2^+[642]$			(408.5) 6.8	
$7/2^+[633]$			902.1 7.36	
$3/2^+[651]$	(7) 324.0[h] 20.1 7.9	(508)		
$1/2^-[521]$		(856) 16.2 0.79		
$3/2^-[532]$	4.8 12.9 > 8.0		202.4 7.49	
$1/2^+[660]$[i]	(9) 91.6 > 9.1	(9) 95.2_{iso}	(9) (132.2) > 6.4	(9) 155.4^{j}_{iso}
$11/2^-[505]$	261.1^{k}_{iso} 14.1	171.2_{iso} 14.8	233.3_{iso} 15.5	
$3/2^+[402]$[l]	306.8 17.7 8.3	212.0 18.2 6.9	240.2 6.29	
$1/2^+[400]$[l]	502.3 14.2 −0.55	328	321.0	
$1/2^-[530]$		(3) (361)	383.6	
$7/2^-$ $\{3/2^-[521]\otimes 2^+\}$			456.1 7.15	
Other levels	m		n	o

[a]Singh *et al.* (1988): NDS; Cook *et al.* (1973): decay; Nelson *et al.* (1971): (d,d'); Graham (1974): (p,d); Nelson *et al.* (1973): (d,t) (d,p), $(^3\mathrm{He},\alpha)$; Vandenput *et al.* (1986): (n,γ), (n,e^-); Cook and Waddington (1973): $(\alpha,n\gamma)$; Cook *et al.* (1976), Gelletly *et al.* (1976): $(\alpha,3n\gamma)$.

[b]Lee (1982): NDS; Tuurnala *et al.* (1974), Alikov *et al.* (1982): decay; Løvhøiden and Burke (1973): (d,t), $(^3\mathrm{He},\alpha)$; Løvhøiden *et al.* (1973): (p,t); Rekstad *et al.* (1981): $(\alpha,n\gamma)$; Katajanheimo *et al.* (1979): $(^3\mathrm{He},4n\gamma)$; Løvhøiden, Hjørth, *et al.* (1972), Rezanka, Bernthal, *et al.* (1972): $(\alpha,3n\gamma)$; Borggreen and Sletten (1970): $(d,2n)$.

[c]Lee (1987): NDS; Abdurazakov *et al.* (1979), Alikov *et al.* (1979), Torres, Paris, and Kilcher (1972): decay; Krein *et al.* (1973): $(^{12}\mathrm{C},3n\gamma)$; Beuscher *et al.* (1975): $(\alpha,5n\gamma)$; Straume, Burke, and Thorsteinsen (1976): (d,t), $(^3\mathrm{He},\alpha)$.

[d]Helmer (1988): NDS; Aguer *et al.* (1977): decay; Grosse *et al.* (1973): $(^{12}\mathrm{C},xn\gamma)$; Beuscher *et al.* (1975): $(\alpha,xn\gamma)$; Holzmann *et al.* (1985): $(^{40}\mathrm{Ar},5n)$.

[e]This transitional nucleus lies on the border of the spherical-deformed shape transition. Calculations by

TABLE XI. (*Continued*).

Vandenput *et al.* (1986) and others show that the positive-parity levels can be understood as Coriolis-mixed rotational bands. The negative-parity levels, however, seem to have a more complex structure, though most of them are described reasonably well by a Coriolis-mixing calculation (Guttormsen *et al.* 1978).

[f]The positive-parity levels are reasonably reproduced in particle-rotor-model calculations. General features of the negative-parity states can also be described. Hoever, in some cases, and in particular for the $5/2^-$[523] band, the cross sections do not agree at all (Straume, Burke and Thorsteinsen, 1976). This nucleus probably has some octupole deformation.

[g]Ekström *et al.* (1969) suggest $3/2^-$[521] or $3/2^+$[651]. If ($9/2^+$, 155.4 keV) level decays to ground state, then $\pi=(-)$ and the $3/2^-$[521] assignment are preferred.

[h]The 3/2 state of this band lies at 345 keV.

[i]Strongly Coriolis-mixed $i_{13/2}$ band. The 9/2 level lies lowest. Interpreted as a decoupled band. The decoupled band structure is not reproduced unless Coriolos-coupling matrix elements are reduced.

[j]The favored ($\alpha=+1/2$) sequence of $i_{13/2}$ mixed positive-parity decoupled band has been identified up to $53/2^+$, but the relative location of the $13/2^+$ level with respect to the ground state is not known.

[k]Martz *et al.* (1985) estimate $\beta_2 \sim 0.26$ for this orbital, while Gelletly *et al.* (1976) give a value $\beta_{\sim}0.35$.

[l]A $\Delta N=2$ mixing with $3/2^+$[651] and $1/2^+$[660] states expected.

[m]Vandenput *et al.* (1986) indicate the existence of many other levels between 355 and 1220 keV.

[n]Torres, Paris, and Kilcher (1972) report a $5/2^+$ level at 247.9 keV and $\log ft=6.9$ lying lower than a $1/2^+$ level at 320.2 keV, tentatively interpreted as the $1/2^+$[660] band. They also report octupole vibrational levels at an energy higher than 1033 keV.

[o]Also observed is a negative-parity band with the lowest state assigned as ($25/2^-$). Again the relative position of the band is not known.

TABLE XII. Intrinsic states of $N=91$ odd-A nuclei.

$N=91$	^{151}Nd[a]	^{153}Sm[b,g]	^{155}Gd[c,g]	^{157}Dy[d]	^{159}Er[e]	^{161}Yb[f]
$3/2^-$[521]	(189.0) 12.1 ~6.0	35.8 11.0 (5.4)[h]	0 12.0 8.8 7.44	0 12.2	0 11.8	0 8.7
$5/2^+$[642]		(194.6) 9.7	266.6 11.9 6.8			
$5/2^-$[523]	531.8[i]		454.5 14.1	341.1 12.7 4.91	220.2 12.4 6.45	
$1/2^-$[521][j] + {$3/2^-$[521]$\otimes 2^+$}	(846.6) ~6.8	695.8 13.6 0.33	559.3 13.6 0.35 9.15	463.5 12.8 0.43		
$7/2^-$[514]					(566.5) 6.8	
$1/2^-$[510]			1078.4 15.3 0.11	(3) (1569) 11.2 −0.12		
$5/2^-$[512]			1343.3 13.5	896.6 13.3 5.9		
$7/2^+$[633]			(13) (1159)			
$1/2^+$[651]			1434.3 6.2 1.14			

TABLE XII. (*Continued*).

$N=91$	^{151}Nd[a]	^{153}Sm[b,g]	^{155}Gd[c,g]	^{157}Dy[d]	^{159}Er[e]	^{161}Yb[f]
$3/2^+[651]$[k]	(0)	0[l]	(5) 86.5[m] 7.9 7.29	(9) 161.9_{iso} 12.3	(13) 225.9[n]	(9) 210.5[o] 7.2
$11/2^-[505]$		98.4_{iso} 11.3	121.5_{iso} 12.4	199.2_{iso} 13.5	428.8	
$3/2^-[532]$	(57.7) 9.6 $\sim$6.1	127.3 11.1 5.8	287.0[p] 6.9 7.95	401.6 10.8		
$3/2^+[402]$		321.1 7.2	268.6 11.5 7.2			
$1/2^-[530]$	(495.2) 5.5 −0.30 $\sim$5.7	(3) (405.5)[q] 8.5 −0.05	(422) 17.5 −0.46	(3) (555) 8.7 0.77		
$1/2^+[400]$		414.9 15.3 0.44	367.6 16.1 0.23 6.97	387		
$1/2^+[660]$		734.9	720.6			
$7/2^+[404]$		1532	1297.2			
$3/2^-$ $\{3/2^-[521]\otimes 0^+\}$			592.1 7.85			
$3/2^+$ $\{3/2^+[651]\otimes 0^+\}$			815.7			
$1/2^-$ $\{3/2^-[521]\otimes 2^+\}$			1003.0			
$1/2^+$ $\{3/2^+[651]\otimes 2^+\}$			1332.1			
Other levels	r	s	t	u		

[a]Singh *et al.* (1988): NDS; Pinston *et al.* (1976): (n,γ), (n,e^-); Katajanheimo, Jäderholm, *et al.* (1984): (d,p).
[b]Lee (1982): NDS; Smither *et al.* (1969): (n,γ), (n,e^-) and decay; Bennett *et al.* (1971): (n,γ), (d,t); Kime (1971): (τ,γ); Kanestrom and Tjöm (1972): (d,t), (d,p); Rekstad *et al.* (1979): $(\alpha,n\gamma)$; Martz *et al.* (1985): (t,α).
[c]Lee (1987): NDS; Kroger and Reich (1975), Meyer *et al.* (1976): decay; Schmidt, von Egidy, *et al.* (1986): (n,γ), (d,p), (d,t); Løvhøiden *et al.* (1970): $(\alpha,3n\gamma)$; Borggreen and Sletten (1970): $(\alpha,n\gamma)$; Løvhøiden *et al.* (1973): (p,t); Løvhøiden *et al.* (1971): $(^3\mathrm{He},\alpha)$; Sterba *et al.* (1971): (d,d'); Tveter and Herskind (1969): Coul.
[d]Helmer (1988): NDS; Torres, Paris, *et al.* (1972): decay; Klamra, Hjørth and Rensfelt (1973): $(\alpha,3n\gamma)$, $(p,3n\gamma)$; Andrejtscheff, Manfrass, Schilling, and Seidel (1974): $(\alpha,2n\gamma)$; Borggreen and Sletten (1970): $(^3\mathrm{He},3n\gamma)$; Grotdal *et al.* (1970): (d,p), (d,t); Beuscher *et al.* (1975): $(\alpha,7n\gamma)$; Grotdal *et al.* (1975): $(^3\mathrm{He},\alpha)$.
[e]Lee (1988): NDS; Strusny *et al.* (1975), Berg *et al.* (1983): decay; Grosse *et al.* (1973): $(^{12}\mathrm{C},3n\gamma)$; Simpson *et al.* (1984): $(^{18}\mathrm{O},4n\gamma)$; Simpson *et al.* (1987): $(^{48}\mathrm{Ca},5n\gamma)$.
[f]Helmer (1984): NDS; Berlovich *et al.* (1980): decay; Hershberger *et al.* (1976): $(^{16}\mathrm{O},3n\gamma)$, $(^{18}\mathrm{O},5n\gamma)$; Riedinger (1980): $(^{16}\mathrm{O},3n\gamma)$.
[g]A small octupole deformation in this nucleus is suggested by Sheline and Sood (1989) (see Fig. 26).
[h]The β intensity to the ground state and 7 keV ($5/2^+$ member of the ground-state band) levels are not known. The logft values are

TABLE XII. (*Continued*).

thus based on the assumption of no feeding to the ground state and the 7 keV levels.

[i]The $5/2^-[523]$ character was earlier assigned to a 542.9-keV level. This level has now been tentatively assigned as the $5/2^-$ member of the $1/2^-[530]$ band.

[j]Theoretical calculations for ^{155}Gd suggest that a vibrational configuration $\{5/2^-[523]\otimes 2^+\}$ may contribute to this state (Soloviev *et al.*, 1967). Strong E2 transitions to the ground-state band also suggest the presence of a $\{3/2^-[521]\otimes 2^+\}$ vibrational state (Schmidt, von Egidy, *et al.*, 1986). The (d,p) cross-section data in ^{153}Sm fit closely to those predicted if this state is only 60% $1/2^-[521]$. The presence of vibrational admixture is strongly supported also in ^{151}Nd and ^{157}Dy.

[k]Highly perturbed due to Coriolis mixing. $\Delta N=2$ mixing with $3/2^+[402]$ state is also possible. The calculations of Kanestrom and Tjöm (1972) show that $\Delta N=2$ interaction plays an important role for the rotational bands built on the $1/2^+[660]$, $3/2^+[651]$, $1/2^+[400]$ and $3/2^+[402]$ states.

[l]The (d,p) and (d,t) cross sections indicate the relative contribution of $3/2^+[402]$ to the ground band and to the 321.1-keV band to be $\approx 16\%$ and $\approx 84\%$, respectively (Bennett *et al.*, 1971; Bunker and Reich, 1971). For detailed calculations in this nucleus see Rekstad *et al.* (1979).

[m]The $3/2^+$ state lies at 105.3 keV.

[n]Riley *et al.* (1984) have extended the $\alpha=+1/2$ sequence of this band up to $85/2^+$ and the $\alpha=-1/2$ sequence up to $43/2^+$. Also observed are the $\alpha=+1/2$ sequence of the ground band up to $69/2^-$ while the $\alpha=-1/2$ branch is seen up to $15/2^-$. One more sideband based on an aligned three-quasiparticle configuration is known at 2260 keV from spin $27/2^-$ to $51/2^-$. Alignment of the first pair of $h_{11/2}$ protons seen in all the bands known to high spin.

[o]The position of $13/2^+$ to $49/2^+$ rotational levels with respect to the $9/2^+$ level is unknown. The moment-of-inertia parameter calculated from 13/2 and 17/2 level energies. This band and the $3/2^-[521]$ band in this nucleus exhibit band crossing at high rotational frequencies. The positive-parity band backbends at a higher rotational frequency than the $3/2^-[521]$ band.

[p]Meyer *et al.* (1976) assigned the levels 321, 393, and 485 keV to the $5/2^-[523]$ band, but Katajanheimo and Hammarén (1979) assigned these levels to the $3/2^-[532]$ band. Recent studies of Schmidt, von Egidy, *et al.* (1986) also support the new assignments.

[q]Malov *et al.* (1970) predict a vibrational admixture of $\{3/2^-[532]\otimes 2^+\}$ in this state.

[r]Other levels observed in (n,γ) lie at 818, 880, 964, 986, 1012, and 1066 keV and presumably have low spin 1/2 and 3/2.

[s]Lien *et al.* (1984) report the observation of strongly populated levels at 698, 1118, and 1708 keV, most likely interpreted as $13/2^+$ states.

[t]A 1028-keV level assigned as $7/2^-$ $\{3/2^-[521]\otimes 2^+\}$, observed earlier in Coulomb excitation studies by Tveter and Herskind (1969), could not be confirmed by Schmidt, von Egidy, *et al.* (1986) and has been removed from this compilation. A 1581-keV level assigned earlier as 11/2, $9/2^-[514]$ also could not be confirmed and was therefore deleted.

[u]Grotdal *et al.* (1970) and Klamra, Hjørth, and Rensfelt (1973) identify additional positive-parity levels at 188.1 ($5/2^+$), 211.2 ($7/2^+$), 234.6 ($3/2^+$), and 308 keV ($3/2^+$). It is possible that they belong to the $(i_{13/2})$ mixed band along with some admixture from $3/2^+[402]$.

TABLE XIII. Intrinsic states of $N=93$ odd-A nuclei.

$N=93$	^{155}Sm[a]	^{157}Gd[b]	^{159}Dy[c]	^{161}Er[d,f]	^{163}Yb[e,g]
$3/2^-[521]$	0 10.6	0 10.9 7.24	0 11.3	0 11.9	0 7.7
$5/2^+[642]$[h]	16.5 8.5	63.8 7.4 7.2	177.6 6.6	(9) 189.4 6.7	99.1
$5/2^-[523]$	426.4 10.5	434.3 11.4 7.17	309.6 12.2 4.87	172.1 13.5 6.8	
$1/2^-[521]$[i]	(819.9) 10.2 −0.21	(702)[j] (11.7) (0.22)	533 12.3 0.43		
$5/2^-[512]$			(1016.3) 10.6 5.40	(843.2)	
$1/2^-[510]$ $+(\{5/2^-[512]\otimes 2^+\})$			(3) 1473 12.3 −0.004		

TABLE XIII. (*Continued*).

$N=93$	^{155}Sm[a]	^{157}Gd[b]	^{159}Dy[c]	^{161}Er[d,f]	^{163}Yb[e,g]
11/2$^-$[505]		425$_{iso}$	352.4$_{iso}$ 14.8	396.4$_{iso}$ 14.0 8.9	
3/2$^+$[402][k] +3/2$^+$[651]	(865.8)[l]			463.1 7.2	
3/2$^+$[651][k] +3/2$^+$[402]	617.5 8.2		417	369.5	
1/2$^+$[400][k]	(903.4) 15.0 0.43	(685)	562	481	
3/2$^-$[532]	778.1 8.6	(762)	627 12.4	(724.8)	
1/2$^-$[530]	(915.5)	(3) (808) (7.2) (0.25)	(3) (749)[m] 6.3 0.20		
1/2$^+$[660][k]	(1282.4)				
3/2$^+$ {3/2$^-$[521]⊗0$^-$}	(1106.7)[n] 9.56				
Other levels		o	p		

[a]Lee (1987): NDS; Greenwood (1982): decay; Groshev *et al.* (1971), Schreckenbach *et al.* (1982): (n,γ); Katajanheimo, Jäderholm, *et al.* (1984): (d,p).
[b]Helmer (1988): NDS; Tayal *et al.* (1986): Coul.; Groshev *et al.* (1971): (n,γ); Sterba *et al.* (1971): (d,d'); Løvhøiden *et al.* (1971): $(^3\mathrm{He},\alpha)$; Tjöm and Elbeck (1967): (d,p), (d,t); Borggreen *et al.* (1967): $(\alpha,n\gamma)$; Løvhøiden *et al.* (1989): (t,p).
[c]Lee (1988): NDS; Boutet *et al.* (1971), Vylov *et al.* (1982): decay; Grotdal *et al.* (1970): (d,p), (d,t); Boutet and Torres (1971), Klamra, Hjørth, *et al.* (1973): $(\alpha,3n\gamma)$; Beuscher *et al.* (1975): $(\alpha,5n\gamma)$.
[d]Helmer (1984): NDS; Borggreen and Sletten (1970): decay (IT); Abdurazakov, Gorozhankin, *et al.* (1980), Adam, Baier, *et al.* (1975): decay; Beuscher *et al.* (1973), Hjørth *et al.* (1970): $(\alpha,3n\gamma)$; Tjöm and Elbek (1969): (d,t); Garrett *et al.* (1982): $(^{16}\mathrm{O},5n\gamma)$.
[e]Burrows (1989): NDS; Richter *et al.* (1977), Richter (1979): $(^{16}\mathrm{O},xn\gamma)$; Kownacki *et al.* (1983): $(^{18}\mathrm{O},4n\gamma)$.
[f]The 3/2$^-$[521] and the positive-parity yrast bands have been observed in this nucleus up to spin 49/2 and 53/2, respectively, and both show backbending. The 11/2$^-$[505] band is observed up to 29/2 and exhibits a rather smooth behavior. The bandcrossing frequencies in these bands differ and have been correlated with a state-dependent pairing (Garrett *et al.* 1982).
[g]A band assigned as 5/2$^-$[523] by Richter (1979) in ^{163}Yb was not established by Kownacki *et al.* (1983). The most striking result from Kownacki *et al.* (1983) is the observation at large rotational frequency of an unfavored configuration $\pi,\alpha=(-,-)$ lying lower in energy than the favored $(-,+)$ configuration.
[h]Highly perturbed band due to Coriolis mixing among the $i_{13/2}$ orbital based bands.
[i]According to Malov *et al.* (1970), this state in ^{153}Sm contains an admixture of {3/2$^-$[521]⊗2$^+$} and {5/2$^-$[523]⊗2$^+$} vibrational states. Some mixing of 1/2$^-$[530] is also possible. We expect the vibrational admixture to be present in this state in all $N=93$ nuclei.
[j]The γ-vibrational admixture in this state may be responsible for the small (d,p) cross sections (Tjöm and Elbek, 1967).
[k]Possible $\Delta N=2$ mixing.
[l]Irregular level spacing clearly indicates $\Delta N=2$ mixing with the 3/2$^+$[651] band. The levels 3/2 and 5/2 lie at 865.8 and 882.1 keV.
[m]The 1/2$^-$ bandhead is not known.
[n]Calculations of Soloviev *et al.* (1983) predict a small component of the octupole state at this energy, and therefore the assignment is tentative.
[o]A tentative assignment of 3/2$^+$[402] bandhead was made earlier to a level at 474.6 keV (Helmer, 1988). A 525-keV level was assigned as the 5/2$^+$ band member giving $A=10.0$ keV. This assignment does not fit into the systematics. Moreover, the 3/2$^+$[402] band is seen to exhibit an irregular spacing in neighboring nuclei which is not seen here. We therefore consider this assignment as tentative.
[p]A 549-keV peak tentatively assigned as 3/2$^+$[651] from the (d,p), (d,t) data may be the {3/2$^+$[402]+3/2$^+$[651]} state.

TABLE XIV. Intrinsic states of $N=95$ odd-A nuclei.

$N=95$	$^{159}Gd^{a}$	$^{161}Dy^{b}$	$^{163}Er^{c,n}$	$^{165}Yb^{d}$
5/2⁻[523]	146.4 11.6 6.7	25.7 11.1 7.8 4.9	0 12.0	0 12.5
1/2⁻[521][e]	507.7 11.5 0.46	366.4 11.8 0.44 8.4	345.7 13.3 0.47 6.6	
5/2⁻[512]	872.7 10.8 7.0	790.7 11.4 5.2	609 12.8 >8.1	
1/2⁻[510]	(3) (1603.2) 11.6 0.34	(1268.6) 11.7 −0.05	1074[f] 12.5 −0.36 6.4	
3/2⁻[512]		1977 12.4		
1/2⁺[651]	(1979.5)[g] (7.0) (−0.45)			
3/2⁻[521]	0 10.1	74.6 11.4 6.8	104.3 12.0 6.6	130[h] 12.6
5/2⁺[642][i]	67.8 7.3 7.0	0 6.3 7.7	69.2 3.2	(9) 126.8 7.5
11/2⁻[505]	682	484	(443.8) 13.2	
3/2⁺[402][j] +3/2⁺[651]	744.4 7.0	680 10.2		
1/2⁺[660][j] +1/2⁺[400]	782.3 13.0 4.6	607.6[k]		
3/2⁺[651][j] +3/2⁺[402]		550.2 11.5 6.3	619.4 9.1	
1/2⁺[400][j] +1/2⁺[660]	973.7	772.7[k]	540.5 20.4 0.12 7.7	
3/2⁻[532]	1110.7 10.3			
1/2⁻[530]	(3) 1145.4[l]	(3) 858.7[l]	816.4 8.1 0.56 6.6	
7/2⁺[404]	1960	(1419)[m]		
1/2⁻ {3/2⁻[521]⊗2⁺}		777		

TABLE XIV. (*Continued*).

$N=95$	^{159}Gd[a]	^{161}Dy[b]	^{163}Er[c,n]	^{165}Yb[d]
			(683.8)	
$1/2^-$			11.8 −0.052	
$\{5/2^-[523]\otimes 2^+\}$				
Other levels		o	p	

[a]Lee (1988): NDS; Kemnitz *et al.* (1969): decay; Peng *et al.* (1976): (d,t); Bonitz and Hansen (1968): (d,p); Groshev *et al.* (1971): (n,γ); Løvhøiden *et al.* (1989): (t,p).
[b]Helmer (1984): NDS; Prasad and Nielsen (1974), Vylov *et al.* (1984): decay; Hjørth *et al.* (1972): $(\alpha,3n\gamma)$; Bennett and Sheline (1977), Schmidt, Stöffl, *et al.* (1986): (n,γ), (d,p), (d,t); Grotdal *et al.* (1970): (d,p); Brown *et al.* (1978), Oshima *et al.* (1988): Coul.; Peng *et al.* (1976): (d,t).
[c]Burrows (1989): NDS; Abdurazakov, Gorozhankin, *et al.* (1980), Abdurazakov *et al.* (1976), Andrejtscheff, Manfrass, Prade, *et al.* (1974), Gnatovich *et al.* (1967): decay; Bacelar, Diebel, Andersen, *et al.* (1985): $(^{18}O,5r\gamma)$; Tjöm and Elbek (1969): (d,p), (d,t); Hjørth *et al.* (1970): $(\alpha,2n\gamma)$; Fenzl and Imazato (1974): $(^{7}Li,3n\gamma)$.
[d]Peker (1987): NDS; Rastikerder *et al.* (1982): decay; Riedinger *et al.* (1974): $(^{22}Ne,5n\gamma)$; Schuck *et al.* (1984): $(^{40}Ar,5n\gamma)$, $(^{20}Ne,5n\gamma)$; Richter (1979): $(^{16}O,5n\gamma)$; Roy *et al.* (1982): $(^{17}O,4n\gamma)$.
[e]This state is expected to have significant vibrational components of $\{5/2^-[523]\otimes 2^+\}$ and $\{3/2^-[521]\otimes 2^+\}$. Calculations for ^{161}Dy by Malov *et al.* (1970) support this admixture.
[f]The (d,p) data indicate that $\approx$40% of this state is $1/2^-[510]$. Based on Soloviev's calculation, Bunker and Reich (1971) suggest a vibrational admixture of $\{5/2^-[512]\otimes 2^+\}$.
[g]The spin assignments are tentative. The parameters are calculated from level energies 1979 keV (1/2), 1991 keV (3/2), 2042 keV (5/2). The theoretical decoupling parameter is positive for this band.
[h]This state seems to be mixture of $h_{9/2}$ and $f_{7/2}$ shell-model configurations with nearly equal spherical components of $C_{jl}=0.6$.
[i]Highly perturbed $i_{13/2}$ positive-parity band also interpreted as a decoupled band. The assigned character is indicative of the main component.
[j]Considerable $\Delta N=2$ mixing expected.
[k]According to Schmidt, Stöffl, *et al.* (1986), these states also have a component of the γ vibration $\{5/2^+[642]\otimes 2^+\}$ and the octupole vibration $\{3/2^-[521]\otimes 1^-\}$ as indicated by E2 and E1 transitions. Detailed Coriolis and $\Delta N=2$ mixing calculations are required to confirm the grouping of levels as 608 keV (1/2), 633 keV (5/2), 699 keV (3/2), 773 keV (1/2), 826 keV (3/2), and 849 keV (5/2). If we group the first three levels together and the rest together to form two $K=1/2$ bands, we obtain $a=+2.54$ and $a=+0.58$, respectively. This favors the lower energy group of levels as belonging to $1/2^+[660]$ and the other one belonging to $1/2^+[400]$.
[l]The bandhead is unidentified.
[m]A small vibrational admixture of $\{3/2^+[651]\otimes 2^+\}$ is expected.
[n]A 711-keV-level previously proposed to be $3/2^-[532]$ by Bennett and Sheline (1977) could not be confirmed by Schmidt, Stöffl, *et al.* (1986).
[o]Bacelar, Diebel, Andersen, *et al.* (1985) report levels up to high spins in the $5/2^-[523]$, $5/2^+[642]$, and $11/2^-[505]$ bands. Bandcrossings are observed in all the bands. In particular, the late bandcrossing in the $11/2^-[505]$ band remains unexplained on the basis of configuration-dependent pairing arguments used elsewhere.
[p]Among other levels observed are $1/2^+$ (1804 keV) and $3/2^+$ (1540 keV) levels interpreted as belonging to the three-quasiparticle configuration $\{1/2^+[411]_p, 7/2^-[523]_p, 5/2^-[523]_n\}$.

TABLE XV. Intrinsic states of $N=97$ odd-*A* nuclei.

$N=97$	^{161}Gd[a]	^{163}Dy[b]	^{165}Er[c]	^{167}Yb[d,f]	^{169}Hf[e]
	0	0	0	0	(0)
$5/2^-[523]$	10.4	10.5	11.0	11.1	11.1
		4.5		>7.0	
	355	351.1[g]	297.4	188.7	
$1/2^-[521]$	10.9 0.21	10.2 0.23	12.6 0.56	13.6 0.71	
$+\{5/2^-[523]\otimes 2^+\}$			6.73	7.6	
				411.0	
$7/2^-[514]$					
				7.2	

TABLE XV. (*Continued*).

$N=97$	^{161}Gd[a]	^{163}Dy[b]	^{165}Er[c]	^{167}Yb[d,f]	^{169}Hf[e]
$7/2^+[633]$[h]	(9) 510[i] 6.2		(465)	430.8 7.2	
$5/2^-[512]$	≈809[j] 12.1	711.5 12.8	477.7 13.6	(213.2) 7.0	(59.2) 14.2
$1/2^-[510]$[k] $+\{5/2^-[512]\otimes 2^+\}$	1311 11.0 −0.18	1160.5 12.1 −0.025	920.6 13.1 0.06 7.13		
$3/2^-[512]$			(1474) 13.0		
$1/2^+[651]$	1490 (7.3) (−0.50)[l]				
$5/2^+[642]$[h]		250.9 5.3	47.2	29.7 6.7	(7) (28.8)[m]
$3/2^-[521]$	314 10.3[n]	421.8 10.7 6.28	242.9 10.6 8.1	179.7 11.9 <7.5	
$1/2^+[660]$ $+\{5/2^+[642]\otimes 2^+\}$			507.4[o] 6.7 3.12 7.38		
$3/2^+[402]$		859.3[p] 5.9	534.5 7.95		
$11/2^-[505]$		851.1	551.0 11.9		
$1/2^+$ $\{5/2^+[642]\otimes 2^+\}$ $+1/2^+[660]$		737.6 6.2 0.52 5.71			
$1/2^+[400]$		1058.5 8.8 −0.026			
$3/2^+[651]$		1147.5 11.0	853.6 6.79		
$1/2^-[530]$		(3) 1049.1[q] 7.5 −1.29	(3) (1039)[r] 10.2 0.53		
$1/2^-$ $\{5/2^-[523]\otimes 2^+\}$		793.4 10.8 −0.15			
$1/2^+$ $\{5/2^-[523]\otimes 2^-\}$		884.3[s] 9.9 0.71 5.0			
Other levels			t		

TABLE XV. (*Continued*).

[a]Helmer (1984): NDS; Groshev *et al.* (1971): (n,γ); Tjöm and Elbek (1967): (d,p).

[b]Burrows (1989): NDS; Kaffrell and Herrmann (1971), Hopke *et al.* (1968): decay; Tveter and Herskind (1969), Minehara *et al.* (1987): Coul.; Holan *et al.* (1974): (d,p); Løvhøiden *et al.* (1985): (t,p); Schmidt *et al.* (1988): (n,γ), (n,e), (d,p), (d,t); Maher *et al.* (1976): (d,t); Grotdal *et al.* (1975): $(^3He,\alpha)$; Boneva *et al.* (1986): $(n,2\gamma)$.

[c]Peker (1987): NDS; Marguier and Chery (1972), Vylov *et al.* (1982): decay; Hjørth *et al.* (1970): $(\alpha,3n\gamma)$; Bollinger and Thomas (1970): (n,γ); Løvhøiden, Tjöm, and Edvardson (1972): $(^3He,\alpha)$; Stott *et al.* (1975): (p,t).

[d]Abdurazakov *et al.* (1971), Meijer *et al.* (1976): decay; Lindblad (1975): $(\alpha,3n\gamma)$; Roy *et al.* (1982): $(^{17}O,4n\gamma)$; Bacelar, Diebel, Ellegaard, *et al.* (1985): $(^{48}Ca,5n\gamma)$.

[e]Shirley (1982): NDS; Rezanka *et al.* (1975): decay, $(^{14}N,4n\gamma)$.

[f]Bacelar, Diebel, Ellegaard, *et al.* (1985) have extended the favored and unfavored sequence of $5/2^+[642]$ and the favored sequence of the ground band up to $73/2^+$, $51/2^+$, and $69/2^-$, respectively.

[g]The small value of the decoupling parameter ($a=0.23$), large B(E2)'s, and branching ratios to the ground state indicate the presence of a vibrational component. The (d,t) and (d,p) cross sections also support the vibrational admixture.

[h]Strongly Coriolis-mixed bands.

[i]The configuration $7/2^+[633]$ bandhead was not observed. Based on other band members, the bandhead is calculated to lie near 446 keV; therefore it may be mixed in the 438-keV level of the 355-keV, $K=1/2$ band. The value of $\hbar^2/2\mathfrak{J}$ is calculated from the 9/2 and 11/2 levels at 510 and ~ 585 keV, respectively.

[j]Helmer (1984) has assigned an energy ~ 809 keV to this state, based on its spin $5/2^-$ as measured in (d,p). The most likely candidate from (n,γ) appears to be the 804.3-keV level.

[k]A small value of the decoupling parameter and the (d,p) cross-sections data, where available, suggest the presence of a vibrational admixture. Calculations of Malov *et al.* (1970) suggest the admixture of the $\{5/2^-[512]\otimes 2^+\}$ state. A mixing with the $1/2^-[521]$ state is also possible.

[l]Calculated from the level energies 1490 keV ($1/2^+$), 1501 keV ($3/2^+$), and 1558 keV ($5/2^+$), the spin assignments being tentative. The theoretical value of the decoupling parameter is positive, which makes the assignments doubtful.

[m]The $5/2^+$ and the $9/2^+$ levels lie at 38.2 and 34.7 keV, respectively. It is highly interesting to note that the favored sequence $(\pi,\alpha=+,+1/2)$, which usually lies lower in energy relative to the unfavored sequence $(\pi,\alpha=+,-1/2)$, has been pushed up here. This makes the spin assignments doubtful.

[n]Calculated from 3/2 and 7/2 levels lying at 314 and 438 keV, respectively.

[o]A small γ-vibrational component of $\{5/2^+[642]\otimes 2^+\}$ is expected in this state.

[p]Bunker and Reich (1971) and Kaffrell and Herrmann (1971) suggest the configuration to be $3/2^+[402]+\{3/2^+[651]+7/2^+[633]\otimes 2^+\}$.

[q]The 1/2 level lies at 1055.8 keV.

[r]The bandhead is not identified.

[s]Because of an au β transition to this state, Kaffrell and Herrmann (1971) interpret this state as having a high contribution of the three-quasiparticle configuration $\{3/2^+[411]_p, 7/2^-[523]_p, 5/2^-[523]_n\}$.

[t]According to Soloviev *et al.* (1967), the γ-vibrational components based on $5/2^+[642]$ and $3/2^+[651]$ are expected to contribute strongly to a level at 745.7 keV, which was earlier assigned as $\{1/2^+[660]+1/2^+[400]\}$. However, its true character is not clear.

TABLE XVI. Intrinsic states of $N=99$ odd-A nuclei.

$N=99$	^{165}Dy[a]		^{167}Er[b]		^{169}Yb[c]		^{171}Hf[d]		^{173}W[e]	
$7/2^+[633]$[f]	0 9.3		0 8.8 6.6		0 7.9		0 6.9		$85.4+x$ 8.0	
$1/2^-[521]$	108.2_{iso} 10.6 ~ 6.3	 0.58	207.8_{iso} 11.2 6.5	 0.70	24.2_{iso} 11.7	 0.79	22.0 12.5	 0.78	$0+y$[g] 14.0	 0.72
$5/2^-[512]$	184.2 10.1 6.8		346.5 11.9 5.8	 9.4	191.2 12.5	 8.71	49.6 13.2		$0+x$[g] 13.6	
$1/2^-[510]+\{5/2^-[512]\otimes 2^+\}$	570.2[h] 11.1	 0.05	763.5 11.7	 0.06	(813.4)[i]					
$7/2^-[514]$			1173		(960.6)					

TABLE XVI. (*Continued*).

$N=99$	^{165}Dy[a]	^{167}Er[b]	^{169}Yb[c]	^{171}Hf[d]	^{173}W[e]
3/2$^-$[512]+ ({7/2$^-$[514]⊗2$^+$})		1384.4			
5/2$^-$[523]	533.5 (10.6)	667.9 11.1 4.5	569.8 11.1 8.73		
3/2$^-$[521]+ {1/2$^-$[521]⊗2$^+$}	573.6 11.0	752.8 11.5	659.6[i] 12.5 10.34		
5/2$^+$[642]		812.5 8.8	(590.7)[j] 8.1 9.14		
11/2$^-$[505]		1052	929.1		
3/2$^+$[402]		1086			
1/2$^+$[400]		1135			
3/2$^+$ {7/2$^+$[633]⊗2$^+$} +3/2$^+$[651]	538.8 9.1 ~6.5	531.5[k] 8.5 7.2	719.9[i] 8.4		
11/2$^+$ {7/2$^+$[633]⊗2$^+$}		711			
7/2$^+$ {7/2$^+$[633]⊗0$^+$}			1070.8		
1/2$^-$ {5/2$^-$[512]⊗2$^+$} +1/2$^-$[510]			1319.8[i] 9.6 0.06		
Other levels	l	m	n		

[a]Peker (1987): NDS; Greenwood *et al.* (1983): decay: Islam *et al.* (1983): (n,γ); Grotdal *et al.* (1970): (d,p).

[b]Harmatz (1976): NDS, decay; Song and Maher (1978): (d,t); Michaelis *et al.* (1970): (n,γ); Ohshima *et al.* (1985), Ohshima *et al.* (1982): Coul.; Sterba *et al.* (1973): (d,d'); Tjöm and Elbek (1969): (d,p), (d,t).

[c]Shirley (1982): NDS; Davaa *et al.* (1982), Bonch-Osmolovskaya *et al.* (1978), Batsev *et al.* (1980): decay; Selin *et al.* (1970): $(\alpha,2n\gamma)$; Michaelis *et al.* (1968): (n,γ); Burke *et al.* (1966): (d,p),(d,t); Oothoudt and Hintz (1973): (p,t).

[d]Shirley (1984): NDS; Rezanka *et al.* (1970): ε decay; Rezanka, Rasmussen, *et al.* (1972): $(\alpha,3n\gamma)$, $(^{10}\text{B},4n\gamma)$, $(^{11}\text{B},5n\gamma)$; Dracoulis and Walker (1979): $(^{16}\text{O},5n)$, $(^{13}\text{C},4n)$.

[e]Shirley (1988): NDS; Walker *et al.* (1978): $(^{16}\text{O},4n\gamma)$.

[f]Highly perturbed $i_{13/2}$ band due to Coriolis mixing.

[g]The 5/2$^-$[512] and the 1/2$^-$[521] bands both are strongly populated, and it is not clear which one is the ground state. No transition connecting these two bands is observed, and either of them can be the ground state.

[h]The contribution of single-particle and vibrational components is expected to be ≈50% each.

[i]According to the calculations of Michaelis *et al.* (1968), these states have a large vibrational admixture (~40% to 70%) of the configuration shown in the table. However, the calculations of Davaa *et al.* (1982) give a small γ-vibrational admixture (~10%) for the 660- and 720-keV states; about 55% vibrational admixture is obtained for the 813-keV state, which agrees with the calculations of Michaelis *et al.* (1968). The systematics of γ-vibrational energies suggests that the 813-keV state is less than 50% vibrational and the 1320-keV state is more than 50% vibrational. Recent calculations of Soloviev *et al.* (1983) give only an 11% vibrational component in the 720-keV state, in agreement with Davaa *et al.*

[j]The quasiparticle-phonon model calculations, including a Coriolis interaction by Davaa *et al.* (1982), indicate about 16% admixture of the 3/2$^+$[651] state in the 5/2$^+$[642] state.

TABLE XVI. (*Continued*).

[k]Calculations of Soloviev *et al.* (1983) give only 12% vibrational admixture in this state, a larger part being concentrated in the subsequent level with $K^{\pi}=3/2^{+}$.
[l]Greenwood *et al.* (1983) interpret the states at 1337.1 and 1400.2 keV as the bandhead and first rotational state, respectively, of the octupole vibrational excitation $\{5/2^{-}[523]\otimes 2^{-}\}$. An important component consists of the three-quasiparticle configuration $\{5/2^{-}[523]_n, 3/2^{+}[411]_p, 7/2^{-}[523]_p\}$. The two proton orbitals in this configuration, if coupled to $K^{*}=2^{-}$, represent the major component ($\sim 95\%$) of the $K^{\pi}=2^{-}$ octupole vibrational phonon in this mass region.
[m]Bond *et al.* (1981) report that a state at 1530 keV in ^{167}Er yields γ rays exclusively from the low-lying members of the $7/2^{+}[633]$ band. This observation is consistent with the state being the previously unobserved $13/2^{+}$ member of the $9/2^{+}[624]$ band, as decay of this level is expected to be primarily by high-energy γ rays (≥ 1 MeV) to members of the $K=7/2$ band. This assignment also fits very well with the extension of a band tentatively assigned as $9/2^{+}[624]$ from the (d,d') experiment (Sterba *et al.*, 1973), where only the $9/2^{+}$ and the $11/2^{+}$ members were identified at 1253 and 1382 keV, respectively.
[n]Levels at 1177.0 keV and 1449.8 keV have been tentatively assigned as $9/2^{+}[624]$ and $7/2^{-}[503]$ bandheads by Davaa *et al.* (1982). The $9/2^{-}$ member of the $7/2^{-}[503]$ band is assigned to a level at 1554.9 keV. They also observe levels at 1463.4 keV ($7/2^{-}$) and 1540.7 keV ($9/2^{-}$), which remain unassigned. Many other levels between 1–2 MeV having firm spin and parity values also remain unassigned. Michaelis *et al.* (1968) also identify additional levels at 1033.8 keV, 1110.7 keV, 1204.3 keV, and 1231.4 keV and assign them the configurations $\{1/2^{+}[660]+1/2^{+}[660]\otimes 0^{+}\}$, $\{1/2^{-}[521]\otimes 2^{+}\}$, $\{3/2^{+}[651]+7/2^{+}[633]\otimes 2^{+}\}$, and $\{1/2^{-}[521]\otimes 2^{+}+3/2^{-}[521]\}$, respectively.

TABLE XVII. Intrinsic states of $N=101$ odd-A nuclei.

$N=101$	^{169}Er[a]	^{171}Yb[b]	^{173}Hf[c]	^{175}W[d]	^{177}Os[e]
$1/2^{-}[521]$	0 11.8 0.83	0 12.0 0.85 6.3	0 12.8 0.82	0 13.9 0.79	0 14.1 0.79
$5/2^{-}[512]$	(92.0) 12.1	122.4 11.9	107.2 12.9 7.2	(104.0) 13.1	152.3[f] 12.6
$1/2^{-}[510]+$ $\{5/2^{-}[512]\otimes 2^{+}\}$	(562.0)[g] 11.7 0.06	(954.2) 12.2 0.00			
$7/2^{-}[514]$	(822) 12.0	835.1 12.6 6.7			
$3/2^{-}[512]$	(1081.6)[g]	(1331.2) 12.8			
$9/2^{+}[624]$	13 (1150)	935.3 7.8			
$7/2^{-}[503]$		1377.5			
$7/2^{+}[633]$[h]	243.4 8.2	95.3_{iso} 8.0 8.1	197.5 6.4 7.6	(235.0)	300.6[f]
$3/2^{-}[521]+$ $\{1/2^{-}[521]\otimes 2^{+}\}$	(714.6)[h] 11.0	902.3 11.2 9.1			
$5/2^{-}[523]$	(853) ~12.4 4.8				

TABLE XVII. (*Continued*).

$N=101$	^{169}Er[a]	^{171}Yb[b]	^{173}Hf[c]	^{175}W[d]	^{177}Os[e]
11/2$^-$[505]	1394	(980.9) 10.2			
5/2$^+$[642]		(9) (984.1)[i]			
3/2$^+$[651]		(9) (1093.3)			
Other levels	j	k			

[a]Shirley (1982): NDS; Haustein and Tucker (1971): decay; Mulligan *et al.* (1970): (d,p), (d,t), (n,γ); Garg *et al.* (1976): (n,γ) resonance; Tjöm and Elbek (1969): (d,p), (d,t); Løvhøiden, Tjöm, and Edvardson (1972): (^{3}He,α); Løvhøiden *et al.* (1985): (t,p); Bond *et al.* (1981): (^{16}O,^{15}O), (^{12}C,^{11}C).

[b]Shirley (1984): NDS; Artamonova *et al.* (1975a), Artamonova *et al.* (1975b), Batsev and Bonch-Osmolovskaya (1981), Kracikova *et al.* (1985): decay; Burke *et al.* (1966): (d,p), (d,t); Wallander and Selin (1972), Ritter and Namenson (1971): (n,γ); Lindblad *et al.* (1972): $(\alpha,3n\gamma)$; Oothoudt and Hintz (1973): (p,t); Burke *et al.* (1971): (^{3}He,α).

[c]Shirley (1988): NDS; Rezanka *et al.* (1973): decay; Hultberg *et al.* (1973): $(\alpha,2n\gamma)$; Dracoulis *et al.* (1979): (^{13}C,4$n\gamma$), (^{9}Be,4$n\gamma$).

[d]Walker *et al.* (1978): (^{16}O,4n).

[e]Dracoulis *et al.* (1983): (^{16,17}O,$xn\gamma$).

[f]There is an uncertainty in the excitation energy of the 67-ns isomer at 300.6 keV because of the uncertainty in the excitation energy of the 58±4-ns isomer at 152.3 keV, to which the 67-ns isomer decays.

[g]The (d,p), (d,t) data also suggest considerable γ-vibrational admixture in the 562-, 714-, and 1082-keV states as calculated by Malov *et al.* (1970).

[h]Coriolis perturbed $i_{13/2}$ mixed band.

[i]The 9/2 member of the 5/2$^+$[642] band has been assigned to a 984.06-keV level by Batsev and Bonch-Osmolovskaya (1981), whereas the 5/2 bandhead is tentatively proposed at $\approx$867 keV by Burke *et al.* (1966).

[j]Mulligan *et al.* (1970) observe a level at 860 keV tentatively assigned as a $K^\pi=3/2^+$ band with configuration {7/2$^+$[633]⊗2$^+$}. Løvhøiden *et al.* (1985) report population of a level at 905 keV with an $l=0$ transition in the (t,p) reaction and, therefore, having spin and parity 7/2$^+$. This may represent a fragment of the 7/2$^+$[633] orbital separated from the main component possibly by Coriolis mixing.

[k]An $l=0$ transfer in the (p,t) reaction to a level at 1513 keV indicates a 5/2$^-$ state with 13% of the summed strength of the 5/2$^-$ at 122 keV. Oothoudt and Hintz (1973) make a probable assignment of a $K=0$ core vibration coupled to the 5/2$^-$[512] neutron.

TABLE XVIII. Intrinsic states of $N=103$ odd-*A* nuclei.

$N=103$	^{171}Er[a]	^{173}Yb[b]	^{175}Hf[c]	^{177}W[d]	^{179}Os[e]
5/2$^-$[512]	0 11.2	0 11.2 9.2 >9.2	0 11.6	(113.6)	
7/2$^-$[514]	(531) 12.7	636 12.6 6.5	348.4 14.1 6.9		(145.5) 14.2
1/2$^-$[510] +{5/2$^-$[512]⊗2$^+$}	(706.9)[f] 10.6 −0.08	1030.5 11.8 0.22	867		
3/2$^-$[512]	(904.4) 13.5	(1340.9)[g] 13.0			
9/2$^+$[624][h]	(13) (~971)		643.9 8.4		$(243.0)_{iso}$

TABLE XVIII. (*Continued*).

$N=103$	^{171}Er[a]	^{173}Yb[b]	^{175}Hf[c]	^{177}W[d]	^{179}Os[e]
$7/2^-[503]$		(1867.2)			
$7/2^+[633]$[h]	(359) 6.6	350.7 6.9 8.36	207.4 5.6		
$1/2^-[521]$	197.9 12.0	398.9_{iso} 12.5 0.68 6.3	125.9_{iso} 13.5 0.75	0 14.8 0.79	0 15.8 0.82
$5/2^-[523]$		(9) (1172.5)	(7) (1056) 11.9		
$3/2^-[521]$[i]		(1232.5) 10.8[j]			
$5/2^+[642]$		(13) (1586.9)	732.4 9.1		
$3/2^+[651]$		(5) (1606.5) 7.2			
Other levels	k		l	m	

[a]Shirley (1984): NDS; Alenius *et al.* (1971b): (n,γ); Kreiner *et al.* (1982): $(^{16}O,^{15}O)$; Tjöm and Elbek (1969): (d,p); Bonitz (1969): (d,p); Bond *et al.* (1981): $(^{12}C,^{11}C)$.

[b]Shirley (1988): NDS; Dzhelepov *et al.* (1979): decay; Harmatz and Horen (1975): decay, Coul.; Alenius *et al.* (1971b): (n,γ); Burke *et al.* (1971): $(^3He,\alpha)$; Taras *et al.* (1977): (d,p), (d,t).

[c]Gadzhokov *et al.* (1971): decay; Alenius *et al.* (1971b): (n,γ); Hultberg *et al.* (1973): $(\alpha,3n\gamma)$; Zaitz *et al.* (1973): (d,t); Dracoulis and Walker (1980): $(^9Be,4n\gamma)$.

[d]Harmatz *et al.* (1975), Goudsmit *et al.* (1970): decay.

[e]Browne (1988): NDS; Dracoulis *et al.* (1983): $(^{16}O,4n\gamma)$.

[f]Calculations of Soloviev *et al.* (1967) suggest about 20% admixture of the $\{5/2^-[512]\otimes 2^+\}$ vibration.

[g]An admixture of $\{7/2^-[514]\otimes 2^+\}$ is suggested by Soloviev *et al.* (1967).

[h]Coriolis-mixed $i_{13/2}$ band.

[i]A significant admixture of the $\{1/2^-[521]\otimes 2^+\}$ vibration is expected.

[j]Calculated from the 3/2 (1232.5 keV) and 7/2 (1362.4 keV) level energies.

[k]Bond *et al.* (1981) also observe states which they tentatively assign as the 13/2 member of $11/2^+[615]$ or the 15/2 member of $1/2^-[770]$ for the level at 1560 keV, the 7/2 member of $7/2^-[503]$ at 1750 keV, and the 9/2 member of $9/2^-[505]$ at 1820 keV.

[l]Gadzhokov *et al.* (1971) indicate occurrence of other levels at 1059 keV $(7/2^+)$, 1124 keV $(9/2^+)$, 1467 keV $(7/2^-)$, 1469 keV $(5/2^-)$, and 1606 keV $(9/2^+)$. They are tentatively assigned the configurations $\{7/2^+[633]\otimes 0^+\}$, $\{7/2^+[633]\otimes 0^+\}$, $\{7/2^-[514]\otimes 0^+\}$, $\{5/2^-[512]\otimes 0^+\}$, and $\{9/2^+[624]\otimes 2^+\}$, respectively. Zaitz *et al.* (1973) also identify additional levels at 1046 keV $(7/2^-)$ and 1227 keV $(9/2^-)$, with tentative assignments of $7/2^-[503]$ and $9/2^-[505]$, respectively. A 941-keV level is tentatively identified as the bandhead of the mixed $\{3/2^-[521]+1/2^-[521]\otimes 2^+\}$ band. Dracoulis and Walker (1980) also observe a 1.2-μs isomer at 3015 keV having a tentative assignment of $35/2^-$, which may be a five-quasiparticle state. The lowest energy 5 qp state expected would have the same configuration as the $23/2^-$ 3qp state plus two extra neutrons occupying the $5/2^-[512]$ and $7/2^-[514]$ orbitals.

[m]Bernthal *et al.* (1976) observed the $i_{13/2}$ band in the $(\alpha,xn\gamma)$ reaction up to spin $33/2^+$. The bandhead spin for the $i_{13/2}$ band is 7/2, but its bandhead energy is not known.

TABLE XIX. Intrinsic states of $N=105$ odd-A nuclei.

$N=105$	^{175}Yb[a]	^{177}Hf[b]	^{179}W[c]	^{181}Os[d]
$7/2^-[514]$	0 11.6	0 12.5 6.7 6.7	0 13.3	0 13.7 6.4

TABLE XIX. (*Continued*).

$N=105$	^{175}Yb[a]	^{177}Hf[b]	^{179}W[c]	^{181}Os[d]
$9/2^+[624]$[e]	(267.5) 10.6	321.3 9.6 6.1 8.4	(308.9) 5.8	(107.6)
$1/2^-[510]$	514.9_{iso} 11.6 0.19 6.5	(3) ($\sim$608) (10.3)[f] ($-$0.44)	(634.9) 18.9 $-$0.04	
$3/2^-[512]$	811.1 12.1 7.1	805.7 14.8 $>$10.5		
$7/2^-[503]$		1057.8 6.5		
$1/2^+[651]$	1356.5 8.1 3.29			
$3/2^-[501]$		1434		
$5/2^-[512]$	639.2 8.4 $>$8.5	508.1 14.6 9.8	430.2 14.5 6.5	
$1/2^-[521]$	920.0 13.7 0.75 6.3	560 13.5 0.58	221.9_{iso} 15.2 0.82	g
$7/2^+[633]$	1009.1 9.2	745.9 11.3 8.1	477.3 19.7 6.3	
Other levels	h	i		

[a]Jacobs *et al.* (1970), Funke *et al.* (1969): decay; Alenius *et al.* (1971c): (n,γ); Whineray *et al.* (1970): (d,p); Burke *et al.* (1971): $(^3\text{He},\alpha)$; Burke *et al.* (1966): (d,t); Tarara and Browne (1979): (d,p), (d,t).

[b]Agnihotry *et al.* (1974), Chu *et al.* (1972), Jeltema and Bernthal (1974): decay; Rickey and Sheline (1968): (d,p), (d,t); Hultberg *et al.* (1973): $(\alpha,3n\gamma)$.

[c]Browne (1988): NDS; Arl't *et al.* (1973), Meijer and Konijm (1975): decay; Meijer *et al.* (1975): $(p,3n\gamma)$; Bernthal and Warner (1975): $(\alpha,2n\gamma)$; Bernthal *et al.* (1978): $(^{13}\text{C},4n\gamma)$, $(\alpha,5n\gamma)$; Pedersen *et al.* (1983): $(^{13}\text{C},4n\gamma)$; Lindblad *et al.* (1973b): $(\alpha,3n\gamma)$, $(p,3n\gamma)$; Kleinheinz *et al.* (1973): (d,t).

[d]Firestone (1984): NDS; Ladenbauer-Bellis *et al.* (1978): decay; Neskakis *et al.* (1976), Leider *et al.* (1982), Fahlander and Dracoulis (1982), Kowakami *et al.* (1974): $(\alpha,5n\gamma)$.

[e]Coriolis-mixed $i_{13/2}$ positive-parity band.

[f]The energy of the 1/2 bandhead is estimated to be 567 keV. The band parameters are calculated from 5/2, 7/2, and 9/2 level energies. Such a large negative value of the decoupling parameter is very unusual for the $1/2^-[510]$ band.

[g]The $1/2^-[521]$ band is known in ^{181}Os. However, no transition between the levels of the $1/2^-[521]$ and $7/2^-[514]$ bands has been found. According to Ladenbauer-Bellis *et al.* (1978), this transition energy may be approximately 19.6 keV. It is not very clear which of the two is the ground state. The systematics favors $7/2^-[514]$ as the ground state.

[h]A number of other levels have been observed by Tarara and Browne (1979), which remain either unassigned or tentatively assigned. Alenius *et al.* (1971c) also identify two levels at 1122 keV and 1938 keV, both $I^\pi=3/2^+$, the former having a complex configuration and the latter possibly $3/2^+[642]$ configuration. Whineray *et al.* (1970) make the tentative assignments of $7/2^-[503]$ and $3/2^-[501]$ to levels at 1420 keV and 1354 keV. Vasileva *et al.* (1984) report the observation of a large number of excited states above 1 MeV in the $(n,2\gamma)$ reaction studies.

[i]Rickey and Sheline (1968) observe several other unassigned bands having bandhead spin $3/2^-$, $1/2^-$, $3/2^-$, and $1/2^-$ at energies 1502, 1634, 1666, and 1882 keV, respectively. Chu *et al.* (1972) also identify a $37/2^-$ isometric state of 2740 keV as a five-quasiparticle state having the assignment $\{7/2^-[514]_n, 9/2^+[624]_n, 5/2^-[512]_n, 9/2^-[514]_p, 7/2^+[404]_p\}$.

TABLE XX. Intrinsic states of $N=107$ odd-A nuclei.

$N=107$	^{177}Yb[a]	^{179}Hf[b]	^{181}W[c]	^{183}Os[d]
$9/2^+[624]$[e]	0 11.4	0 11.2 6.64 6.5	0 10.3	0 8.6
$1/2^-[510]$	331.5_{iso} 12.1 0.20	375.0_{iso} 13.2 0.16	457.9[f] 15.0 0.59	395.0 15.7 0.23
$3/2^-[512]$	703 14.2	720.6 13.6	726.3 16.2 7.0	582.0 17.4
$7/2^-[503]$	(1222)	870.2 8.04	661.8 15.9 7.0	392.5 18.4
$3/2^-[521]$		(1269.4)		
$3/2^-[501]$	(1360) 17.4	1459.0		
$7/2^-[514]$	104.5 13.1	214.3 13.5 7.26	409.2 13.2 7.7	512.4 14.9
$5/2^-[512]$		518.3 13.8 10.0	365.6_{iso} 15.7 ~7.2	544.2 15.8
$1/2^-[521]$		614.1 13.0 0.66	385.2[f] 14.7 0.48	170.7_{iso} 16.0 0.82
$7/2^+[633]$		(1105.9) 7.0	953.4 4.4 >7.8	731.5 6.8
$5/2^+$ $\{9/2^+[624]\otimes 2^+\}$		1003.6 10.7		
$9/2^+$ $\{9/2^+[624]\otimes 0^+\}$		(1120.8)		
$1/2^+$ $\{1/2^-[510]\otimes 1^-\}$		1150.4 10.9 0.09		
$3/2^-$ $\{7/2^-[514]\otimes 2^+\}$		1249.5 12.8		
$3/2^+$ $\{1/2^-[521]\otimes 1^-\}$		1482.0		
Other levels			g	

[a]Rykaczewski *et al.* (1988, 1989): decay; Tarara and Browne (1979): (d,p); Alenius *et al.* (1972): (n,γ).
[b]Browne (1988): NDS; Hübel *et al.* (1975): decay (IT); Hill and Meyer (1976): decay; Casten and Kane (1973), Alenius *et al.* (1972): (n,γ); Richter *et al.* (1989): (n,γ), (d,p), (d,t); Thorsteinsen *et al.* (1968): (τ,α).
[c]Firestone (1984): NDS; Daly *et al.* (1971): decay; Lindblad *et al.* (1973a): $(\alpha,2n\gamma)$, $(\alpha,3n\gamma)$; Casten *et al.* (1972): (d,p), (d,t); Kleinheinz *et al.* (1973): $(^3He,\alpha)$; Mortensen *et al.* (1980): (p,t); Bernthal *et al.* (1976): $(\alpha,xn\gamma)$.

TABLE XX. (*Continued*).

[d]Firestone (1987): NDS; Jager *et al.* (1975): $(\alpha,7n\gamma)$; Neskakis *et al.* (1976): $(\alpha,5n\gamma)$; Lindblad *et al.* (1973): $(\alpha,3n\gamma)$; Roussiere *et al.* (1988): decay.
[e]Coriolis-mixed $i_{13/2}$ band.
[f]The two $K=1/2$ bands lying close to each other probably mix strongly with each other, thus changing the decoupling parameter considerably.
[g]Many unassigned levels that lie above 1 MeV are discussed by Daly *et al.* (1971).

TABLE XXI. Intrinsic states of $N=109$ odd-A nuclei.

$N=109$		^{181}Hf[a,d]			^{183}W[b]			^{185}Os[c]	
		0			0			0[e]	
1/2$^-$[510]	12.9		0.18	13.0		0.19	12.2		0.02
						9.22			
		252			208.8			127.9	
3/2$^-$[512]	15.5			16.6			18.9		
	~6.0					7.18			
					309.5$_{\rm iso}$			(275.7)	
11/2$^+$[615]				13.7			10.7		
		(663.9)			453.1			102.3$_{\rm iso}$	
7/2$^-$[503]				15.8			17.6		
	>6.4			6.88		6.76			
		(1495)							
3/2$^-$[501]	11.2								
		(1637)							
5/2$^-$[503]	10.6								
		~600[f]			622.8			(402.6)	
9/2$^+$[624]							17.2		
				7.7					
					(904.5)				
5/2$^-$[512]				13.9					
					(934.6)			(406.6)	
1/2$^-$[521]				17.9		0.70	14.0		0.49
		904.5			(1072)				
7/2$^-$[514]				16.3					
	4.5								
1/2$^-$ {1/2$^-$[510]⊗0$^+$}								(1070)[g]	
Other levels		h			i			j	

[a]Firestone (1984): NDS; Kirchner *et al.* (1982), Rykaczewski *et al.* (1988,1989): decay; Rickey and Sheline (1968): (d,p); Alenius *et al.* (1971a): (n,γ); Burke *et al.*, (1984): (t,p).
[b]Firestone (1987): NDS; McGowan *et al.* (1979): Coul.; Casten *et al.* (1972): (d,p), (d,t); Casten and Kane (1973): (n,γ); Casten *et al.* (1973): (d,p); Flynn *et al.* (1970): (t,d).
[c]Ellis-Akovali (1981c): NDS; Sodan *et al.* (1975): $(\alpha,2n\gamma)$; Prokofjev and Simonova (1974): (n,γ); Sharma and Hintz (1976): (p,t).
[d]An increasing hexadecapole deformation as the neutron number increases results in a change of the

TABLE XXI. (*Continued*).

odd-A neutron-rich Lu isotopes' ground-state configuration from $7/2^+[404]$ to $9/2^-[514]$ and has been confirmed by Rykaczewski *et al.* (1988, 1989). As a result the reported three-quasiparticle states at 905 keV in ^{181}Hf and 1125 keV in ^{183}Hf are now assigned to the one-neutron configuration $7/2^-[514]$. The au fast beta decay of ^{181,183}Lu into ^{181,183}Hf, respectively, occurs due to a change of neutron from the $7/2^-[514]$ state into a proton in the half-occupied $9/2^-[514]$ state of the Lu isotope.

[e]Interband transitions between some members of the bands based on the configurations $1/2^-[510]$ and $7/2^-[503]$ in ^{185}Os indicate a strong mixing of the two $I=13/2$ rotational members, which lie close in energy. This $\Delta K=3$ mixing could be explained by a Coriolis-coupling calculation involving only first-order matrix elements (Sodan *et al.*, 1975).

[f]Only the $l=0$ transition seen in the ^{179}Hf$(t,p)^{181}$Hf reaction is observed to a level at 600±5 keV, requiring this level to be the $9/2^+[624]$ state. The systematics supports this result (Sood *et al.*, 1989). However, no gamma transitions deexciting this level in a $(t,p\gamma)$ experiment were seen. It implies that the 600±5-keV level either has a half-life of ≥ 1 μs or decays to an isomeric level by means of a low-energy (≤ 100 keV) unobserved transition.

[g]A 1123-keV level is probably the $3/2^-$ member of this band.

[h]Many low-spin bands at 1063 keV ($K=3/2^-$), 1267 keV ($K=3/2^-$), 1330 keV ($K=3/2^-$), 1406 keV ($K=1/2^-$), 1745 keV ($K=1/2^-$), and 1799 keV ($K=1/2^-$) are reported by Rickey and Sheline (1968). These bands cannot be interpreted in a simple way in the Nilsson model and seen to have a complex structure. Soloviev's calculations for the complex states do not give any excitations near the experimental data. Alenius *et al.* (1971a), on the other hand, observe many low-spin states between 0.8 MeV and 1.3 MeV, which do not correspond to the states observed in the (d,p) reaction.

[i]Many low-spin ($I<5/2$) states up to ≈ 2.1 MeV are seen in the (n,γ) reaction. Coulomb excitation of many states yields $B(E2)$ values smaller than $B(E2)_{s.p.}$.

[j]Two levels at 599 keV and 802 keV are tentatively assigned as the $3/2^-$ $\{1/2^-[510]\otimes 2^+\}$ and the $5/2^-$ $\{1/2^-[510]\otimes 2^+\}$ states. Many other levels are observed to lie between 0.4 MeV and 1 MeV, but remain unassigned. In particular, Prokofjev and Simonova (1974) observe $(3/2^-)$ levels at 641.5, 843.3, and 1116.2 keV. The 641.5-keV $(3/2^-)$ level is tentatively assigned as $\{7/2^-[503]\otimes 2^+\}$. A 1213-keV level observed by Sharma and Hintz (1976) may be the $1/2^-$ bandhead of the $\{1/2^-[510]\otimes 0^+\}$ band, or the $1/2^-[521]$ band and a 1275-keV level the $3/2^-$ member of this band.

TABLE XXII. Intrinsic states of $N=111$ odd-A nuclei.

$N=111$		^{183}Hf[a,d]			^{185}W[b]			^{187}Os[c]	
		0			0			9.8	
$3/2^-[512]$	13.7			13.2			13.1		
									6.8
					197.4_{iso}			257.3_{iso}	
$11/2^+[615]$				14.3			12.5		
					(785.4)			(445.1)	
$9/2^-[505]$									
				7.5					
								711.3	
$5/2^-[503]$									
									7.0
								987.3	
$3/2^-[501]$									
	(5)	(205.7)			(23.5)			0	
$1/2^-[510]$				21.1		0.10	23.7		0.04
	6.9						11.3		6.8
		(316.9)			243.5			100.7	
$7/2^-[503]$				14.4			18.1		
	6.5			6.4					

TABLE XXII. (*Continued*).

$N=111$	$^{183}Hf^{a,d}$	$^{185}W^{b}$	$^{187}Os^{c}$
$9/2^{+}[624]$		716 12.7	557.1 15.5
$5/2^{-}[512]$		(888) 14.0	
$1/2^{-}[521]$		(1006.9) 17.7 0.86	536.3 14.5 0.38
$7/2^{-}[514]$	1125.3 18.6 <5.4	(1059) ~ 17.8 7.6	1080
$1/2^{-}$ $\{3/2^{-}[512]\otimes 2^{+}\}$		(1013) 7.8 0.15	
$3/2^{-}$ $\{7/2^{-}[503]\otimes 2^{+}\}+$ $3/2^{-}[501]$			501.5[e] 17.0 6.9
Other levels		f	g

[a]Firestone (1987): NDS; Rykaczewski *et al.* (1983), Rykaczewski *et al.* (1988, 1989): decay.
[b]Ellis-Akovali (1981c): NDS; Prade *et al.* (1973), Murray *et al.* (1969): (n,γ); Casten *et al.* (1973): $(\mathbf{d}p)$; Ascuitto *et al.* (1974): (p,d); Casten *et al.* (1972): (d,t), (d,p); Kleinheinz *et al.* (1973): (d,t).
[c]Ellis-Akovali (1982): NDS; Malmskog *et al.* (1971), Ahlgren and Daly (1972): decay; Sodan *et al.* (1975): $(d,2n\gamma)$, $(p,n\gamma)$; Morgen *et al.* (1973): (d,p), (d,t), (d,d'); Prokofjev and Simonova (1974): (n,γ); Thompson and Sheline (1973): (d,t); Sharma and Hintz (1976): (p,t).
[d]See comment *d* for ^{181}Hf.
[e]This is the most probable assignment. Thompson and Sheline (1973) assigned this as the $3/2^{-}$, $\{1/2^{-}[510]\otimes 2^{+}+3/2^{-}[512]\}$ state.
[f]Among other levels observed by Casten *et al.* (1973) are 666 keV ($3/2^{-},5/2^{-}$), 1184 keV ($1/2^{-}$ or $1/2^{+},3/2^{+}$) with possible configuration $1/2^{-}[510]$, and 1222 keV ($3/2^{-}$) with possible configuration $3/2^{-}[501]$.
[g]Two levels at 664.1 keV and 725.6 keV are tentatively identified as $5/2^{-}$, $\{1/2^{-}[510]\otimes 2^{+}+5/2^{-}[512]\}$, and $3/2^{-}$, $\{1/2^{-}[510]\otimes 2^{+}+3/2^{-}[512]\}$ by Sharma and Hintz (1976). Ahlgren and Daly (1972) also propose a level at 941.2 keV, which they consider a $5/2^{+}$ level originating from $N=6$. Many other levels between 0.4 MeV and 2 MeV are known and remain unassigned.

TABLE XXIII. Intrinsic states of $N=113$, 115, and 117 odd-A nuclei.

$N=113$	$^{187}W^{a}$	$^{189}Os^{b}$	$N=115$	$^{191}Os^{c}$	$N=117$	$^{193}Os^{d,i}$
$3/2^{-}[512]^{e}$	0 15.5	0 13.9 7.12 7.1		74.4_{iso} 11.9		0 16.0
$11/2^{+}[615]$	(13) (366)	(13) (290.5)		(13) (351)		
$9/2^{-}[505]$	(598)	30.8_{iso}		0		

TABLE XXIII. (*Continued*).

$N=113$	$^{187}W^{a}$		$^{189}Os^{b}$		$N=115$	$^{191}Os^{c}$	$N=117$	$^{193}Os^{d,i}$
	(640.5)							
$5/2^{-}[503]$								
	782.4							
$1/2^{-}[501]$								
	145.8		36.2			(84.4)		41.5
$1/2^{-}[510]^{e}$	19.7	0.00	23.7	−0.17				
			>9.4	>7.9				
	(350.3)		(216.7)			(462.8)		
$7/2^{-}[503]$								
			7.4	9.4				
Other levels	f		g			h		

[a]Ellis-Akovali (1982): NDS; Casten *et al.* (1974): (n,γ); Stecher-Rasmussen *et al.* (1972): $(\mathbf{n},\gamma)$; Casten *et al.* (1973): $(\mathbf{d},p)$.
[b]Firestone (1981): NDS; Sakaguchi *et al.* (1979), Malmskog, Berg, and Bäcklin (1970), Hofstetter (1973): decay; Benson *et al.* (1976): (d,p), (d,t), (n,γ); Morgen *et al.* (1975): (d,p), (d,t), (d,d'); Jha *et al.* (1983): Coul.
[c]Browne (1989): NDS; Benson *et al.* (1977): (d,p), (d,t), (n,γ); Casten *et al.* (1977): (n,γ).
[d]Shirley (1981): NDS; Warner *et al.* (1979): (n,γ); Bensen *et al.* (1978): (d,p), (n,γ).
[e]$3/2^{-}[512]$ and $1/2^{-}[510]$ bands are strongly Coriolis coupled.
[f]From the high angular momentum transfer in the (d,p) reaction and systematics, Casten *et al.* (1972) suggested that levels at 366 and 598 keV are probably the $13/2^{+}$, $11/2^{+}[615]$ and $9/2^{-}$, $9/2^{-}[505]$ states; they cautioned that these assignments could be reversed. Many other levels lying between 0.5 MeV and 2 MeV are known and remain unassigned.
[g]Morgen *et al.* (1975) suggest the assignments 7/2, $7/2^{-}[514]$ and 5/2, $5/2^{-}[512]$ to levels populated at 813 and 526 keV, respectively. Benson *et al.* (1976) assign a 688-keV level as the bandhead of $1/2^{-}[521]$ in contrast to Morgen *et al.* (1975) and Sakaguchi *et al.* (1979), who make the same assignment to a level at 438 keV. In addition, many levels are known, as low as 276 keV, which do not fit into the simple Nilsson-model predictions.
[h]Benson *et al.* (1977) observe $K^{\pi}=3/2^{-}$ and $5/2^{-}$ at energies 418 and 273 keV.
[i]Identification of the excited states with the Nilsson orbitals is qualitative in nature. Strong Coriolis interaction is expected in such weakly deformed nuclei.

TABLE XXIV. Three-quasiparticle excitations in odd-Z rare-earth nuclei.

Nucleus	K^{π}	Configuration	Energy (keV)	A (keV)	$\beta^{\rightleftarrows}$	References and comments
^{175}Lu	$19/2^{+}$	$(\{7/2^{+}[404]_p, 7/2^{-}[514]_n, 5/2^{-}[512]_n\})$	1401			a
	$9/2^{+}$	$(\{7/2^{+}[404]_p, 7/2^{-}[514]_n, 5/2^{-}[512]_n\})$	1511			
	$13/2^{+}$	$(\{7/2^{+}[404]_p, 7/2^{-}[514]_n, 1/2^{-}[521]_n\})$	1590			
	$15/2^{+}$	$(\{7/2^{+}[404]_p, 7/2^{-}[514]_n, 1/2^{-}[521]_n\})$	1732			
^{177}Lu	$23/2^{-}$	$\{7/2^{+}[404]_p, 7/2^{-}[514]_n, 9/2^{+}[624]_n\}$	970.2	10.8		b,i
	$11/2^{+}$	$\{9/2^{-}[514]_p, 7/2^{-}[514]_n, 9/2^{+}[624]_n\}$	1230.7		$\beta^{\rightarrow}$ (4.3)	
	$(7/2^{+})$	$\{9/2^{-}[514]_p, 7/2^{-}[514]_n, 9/2^{+}[624]_n\}$	1241		$\beta^{\rightarrow}$ (4.4)	
	$7/2^{+}$	$\{9/2^{-}[514]_p, 7/2^{-}[514]_n, 9/2^{+}[624]_n\}$	1336		$\beta^{\rightarrow}$ (5.05)	
	$15/2^{+}$	$\{7/2^{+}[404]_p, 7/2^{-}[514]_n, 1/2^{-}[510]_n\}$	1356.9	10.0		
	$(13/2^{+})$	$(\{7/2^{+}[404]_p, 7/2^{-}[514]_n, 1/2^{-}[521]_n\})$	1453.6	10.2		
	$13/2^{+}$	$\{7/2^{+}[404]_p, 7/2^{-}[514]_n, 1/2^{-}[510]_n\}$	1502.6	11.6		
	$(15/2^{+})$	$(\{7/2^{+}[404]_p, 7/2^{-}[514]_n, 1/2^{-}[521]_n\})$	1631.6	10.6		
^{173}Ta	$(21/2^{-})$	$(\{9/2^{-}[514]_p, 7/2^{-}[514]_n, 5/2^{-}[512]_n\})$	1713			c,j
^{175}Ta	$21/2^{-}$	$(\{9/2^{-}[514]_p, 7/2^{-}[514]_n, 5/2^{-}[512]_n\})$	1569			d,k
^{177}Ta	$3/2^{-}$	$\{9/2^{-}[514]_p, 7/2^{-}[514]_n, 1/2^{-}[512]_n\}$	1253.0		$\beta^{\leftarrow}$(5.6)	e
	$21/2^{-}$	$(\{9/2^{-}[514]_p, 7/2^{-}[514]_n, 5/2^{-}[512]_n\})$	1355.2	11.8		l

TABLE XXIV. (*Continued*).

Nucleus	K^π	Configuration	Energy (keV)	A (keV)	$\beta^{\rightleftarrows}$	References and comments
	$(1/2^-)$	$(\{9/2^-[514]_p,\ 7/2^-[514]_n,\ 5/2^-[512]_n\})$	1512.3		$\beta^{\leftarrow}(5.4)$	
	$(21/2^-)$	$(\{9/2^-[514]_p,\ 7/2^+[404]_p,\ 5/2^+[402]_p\})$	(1696)	10.8		
	$23/2^+$	$\{9/2^-[514]_p,\ 9/2^+[624]_n,\ 5/2^-[512]_n\}$	1698.6			
	$25/2^+$	$\{9/2^-[514]_p,\ 9/2^+[624]_n,\ 7/2^-[514]_n\}$	1834.9	7.5		
	$25/2^-$	$\{9/2^-[514]_p,\ 9/2^+[624]_n,\ 7/2^+[633]_n\}$	2098.8			
^{179}Ta	$21/2^-$	$\{9/2^-[514]_p,\ 7/2^+[404]_p,\ 5/2^+[402]_p\}$	1253.1	12.6		f,m
	$25/2^+$	$\{9/2^-[514]_p,\ 9/2^+[624]_n,\ 7/2^-[514]_n\}$	1317.8	10.1		
	$23/2^-$	$\{7/2^+[404]_p,\ 9/2^+[624]_n,\ 7/2^-[514]_n\}$	1328.4	11.0		
^{183}Ta	$5/2^-$	$\{9/2^-[514]_p,\ 7/2^-[514]_n,\ 3/2^-[512]_n\}$	1543.4		$\beta^{\rightarrow}(5.84)$	g
^{183}Re	$(25/2^+)$	$\{5/2^+[402]_p,\ 9/2^+[624]_n,\ 11/2^+[615]_n\}$	1907.6			g,h
	$(11/2^+)$	$(\{9/2^-[514]_p,\ 9/2^+[624]_n,\ 7/2^-[514]_n\})$	2030.0		$\beta^{\leftarrow}(7.1)$	

[a]Minor *et al.* (1971).
[b]Minor *et al.* (1971), Manfrass *et al.* (1971), Geinoz *et al.* (1975).
[c]André, Barneoud, *et al.* (1977).
[d]Foin *et al.* (1972).
[e]Barneoud *et al.* (1975).
[f]Manfrass *et al.* (1974), Barneoud *et al.* (1982).
[g]Firestone (1987).
[h]Brenner *et al.* (1983).
[i]Another strongly populated level at 1974 keV is also tentatively interpreted as a three-quasiparticle state with assignment $17/2^+$ $\{7/2^+[404]_p, 7/2^-[514]_n, 3/2^-[512]_n\}$ by Minor *et al.* (1971).
[j]This state is proposed by André, Barneoud, *et al.* (1977) from the analysis of timing and coincidence experiments. This level with a half-life of 100-ns decays to the $K^\pi=9/2^-$ band by means of three γ rays of 356, 609, and 840 keV. The possibilities for spin and parity are $19/2^+$ and $21/2^-$, but systematics suggests $K^\pi=21/2^-$ and this configuration.
[k]The presence of a delayed component in some transitions within the $9/2^-[514]$ rotational band and γ-γ coincidence measurements indicate the existence of an isomeric level at 1569 keV with probable half-life of 200±70 ns and spin 21/2, here interpreted as a three-quasiparticle state.
[l]Aoki *et al.* (1982) calculate g_k factors for all the possible configurations for $K^\pi=21/2^-$ and conclude that the configuration of the 1355-keV state should be $\{7/2^+[404]_p, 5/2^-[512]_n, 9/2^+[624]_n\}$.
[m]The $21/2^-$ state is probably a mixture of many configurations. In addition, Barneoud *et al.* (1982) also report two states at 2640.6 keV ($37/2^+$) and 2794.1 keV ($33/2^-$) as possibly having five-quasiparticle configurations. Probable assignments are $37/2^+$: coupling of $5/2^+[402]_p$ to the 16^+ four-quasiparticle state of the core $\{9/2^+[624]_n, 7/2^-[514]_n, 9/2^-[514]_p, 7/2^+[404]_p\}$; and for $33/2^-$: a mixed configuration with the main component being a coupling of $1/2^-[541]_p$ to $\{9/2^+[624]_n, 7/2^-[514]_n, 9/2^-[514]_p, 7/2^+[404]_p\}$.

TABLE XXV. Three-quasiparticle excitations in odd-N rare-earth nuclei.

Nucleus	K^π	Configuration	Energy (keV)	A (keV)	$\beta^{\rightleftarrows}$	References and comments
^{165}Dy	$(1/2)^+$	$\{3/2^+[411]_p,\ 7/2^-[523]_p,\ 5/2^-[523]_n\}$	1773.1		$\beta^{\rightarrow}(5.0)$	a
^{163}Er	$3/2^+$	$\{1/2^+[411]_p,\ 7/2^-[523]_p,\ 5/2^-[523]_n\}$	1538.4		$\beta^{\leftarrow}(5.1)$	b
	$1/2^+$	$(\{1/2^+[411]_p,\ 7/2^-[523]_p,\ 5/2^-[523]_n\})$	1802.0		$\beta^{\leftarrow}(4.9)$	
^{165}Er	$3/2^+$	$\{1/2^+[411]_p,\ 7/2^-[523]_p,\ 5/2^-[523]_n\}$	1427.5		$\beta^{\leftarrow}(5.41)$	c
^{165}Yb	$5/2^+$	$\{5/2^-[523]_n,\ 7/2^-[523]_p,\ 7/2^+[404]_p\}$	1734.1		$\beta^{\leftarrow}(4.4)$	a,l
	$5/2^+$	$\{5/2^-[523]_n,\ 7/2^-[523]_p,\ 7/2^+[404]_p\}$	2125.9		$\beta^{\leftarrow}(4.1)$	l
^{167}Yb	$5/2^+$	$\{5/2^-[523]_n,\ 7/2^-[523]_p,\ 7/2^+[404]_p\}$	1507		$\beta^{\leftarrow}(5.5)$	d

TABLE XXV. (*Continued*).

Nucleus	K^π	Configuration	Energy (keV)	A (keV)	$\beta^{\rightleftarrows}$	References and comments
^{175}Yb	3/2$^+$	$\{7/2^-[514]_n,\ 9/2^-[514]_p,\ 1/2^+[411]_p\}$	1497		$\beta^{\rightarrow}(5.0)$	e
	1/2$^+$	$\{7/2^-[514]_n,\ 9/2^-[514]_p,\ 1/2^+[411]_p\}$	1891		$\beta^{\rightarrow}(4.8)$	
	3/2$^+$	$(\{5/2^-[523]_n,\ 7/2^-[523]_p,\ 1/2^+[411]_p\})$	1792		$\beta^{\rightarrow}(5.5)$	
	1/2$^+$	$(\{5/2^-[523]_n,\ 7/2^-[523]_p,\ 1/2^+[411]_p\})$	2113		$\beta^{\rightarrow}(5.2)$	
^{171}Hf	19/2$^+$	$\{5/2^+[402]_p,\ 7/2^+[404]_p,\ 7/2^+[633]_n\}$	1645.1	7.1		f
	23/2$^-$	$\{9/2^-[514]_p,\ 7/2^+[404]_p,\ 7/2^+[633]_n\}$	1984.6	7.1		
^{173}Hf	19/2$^+$	$\{5/2^+[402]_p,\ 7/2^+[404]_p,\ 7/2^+[633]_n\}$	1702	5.6		g
	23/2$^-$	$\{9/2^-[514]_p,\ 7/2^+[404]_p,\ 7/2^+[633]_n\}$	1985			m
^{175}Hf	19/2$^+$	$\{5/2^+[402]_p,\ 7/2^+[404]_p,\ 7/2^+[633]_n\}$	1433	5.3		h,n
	23/2$^-$	$\{9/2^-[514]_p,\ 7/2^+[404]_p,\ 7/2^+[633]_n\}$	1766	5.5		
^{177}Hf	23/2$^+$	$\{9/2^-[514]_p,\ 7/2^+[404]_p,\ 7/2^-[514]_n\}$	1315.4	11.1	$\beta^{\rightarrow}(6.4)$	i,o
^{179}Hf	25/2$^-$	$\{9/2^-[514]_p,\ 7/2^+[404]_p,\ 9/2^+[624]_n\}$	1105.7			j
^{179}W	3/2$^+$	$\{9/2^-[514]_p,\ 5/2^+[402]_p,\ 7/2^-[514]_n\}$	720.2	10.7	$\beta^{\leftarrow}(5.2)$	k,p,q
	7/2$^+$	$\{9/2^-[514]_p,\ 5/2^+[402]_p,\ 7/2^-[514]_n\}$	1680.1		$\beta^{\leftarrow}(5.1)$	q

[a]Greenwood *et al.* (1983).
[b]Meijer (1976), Gnatovich *et al.* (1967).
[c]Marguier and Chery (1972), Vylov *et al.* (1982).
[d]Abdurazakov *et al.* (1971).
[e]Funke *et al.* (1969).
[f]Dracoulis and Walker (1979).
[g]Dracoulis *et al.* (1979).
[h]Dracoulis and Walker (1980).
[i]Chu *et al.* (1972), Hultberg *et al.* (1973).
[j]Hübel *et al.* (1975).
[k]Arl't *et al.* (1973), Meijer and Konijn (1975).
[l]These two states are supposedly highly mixed with each other.
[m]The excitation energies of the 1702 keV and the 1895 keV states are similar to the 8^- and 6^+ two-quasineutron states in the core nucleus ^{172}Hf, indicating a decoupling of the $7/2^+[633]$ neutron.
[n]A 1.2-μs isomeric state at 3015 keV is tentatively assigned a five-quasiparticle configuration resulting from a coupling of two neutrons in the $5/2^-[512]$ and $7/2^-[514]$ orbitals to the $23/2^-$ three-quasiparticle state.
[o]A $37/2^-$ isomeric state at 2740 keV is probably a five-quasiparticle state obtained by a coupling of two neutrons in the $9/2^+[624]$ and $5/2^-[512]$ orbitals to the $23/2^+$ three-quasiparticle state.
[p]Additional multi-quasiparticle structures are reported by Bernthal *et al.* (1978) and Pedersen *et al.* (1983). A level at 1632 keV ($K^\pi=21/2^+$) and another at 1832.7 keV ($K^\pi=23/2^-$) are possibly three-quasiparticle states having assignments of $\{7/2^-[514]_n,\ 9/2^+[624]_n,\ 5/2^-[512]_n\}$ and $\{7/2^-[514]_n,\ 9/2^+[624]_n,\ 7/2^+[633]_n\}$, respectively. A 710-ns isomer is tentatively assigned K^π, $I=35/2^-$, 35/2, a very short lifetime for a state that decays into the $K=7/2$ ground-band rotational member with $I=31/2$. An accidental degeneracy of this level with the $35/2^-$ member of the ground band has been used by Pedersen *et al.* (1983) to explain the short lifetime. In total, four five-quasiparticle states tentatively proposed are $K^\pi=35/2^-$, (3348.7 keV), $K=37/2$ (3582.6 keV), $K=37/2$ (3596.8 keV), and $K=39/2$ (3778.7 keV), which are all interpreted as deformation-aligned states.
[q]A low logft value for an au transition suggests this three-quasiparticle configuration as a significant component. A 773.3-keV ($5/2^+$) level is suggested to be the first member of the rotational band built on the 720.2-keV state.

TABLE XXVI. Decoupling parameter values for $K=1/2$ states in odd-Z rare-earth nuclei. In the second column A denotes the mass number.

State configuration	Calculated[a] A	a	Empirical Nucleus	a	Nucleus	a
$1/2^+[411]$	154	−0.97	^{151}Pm	−0.48	^{171}Tm	−0.86
	164	−0.93	^{155}Eu	−1.29	^{173}Tm	−0.93
	178	−1.07	^{159}Tb	−0.83	^{175}Tm	−0.99
	186	−1.11	^{159}Ho	−0.80	^{169}Lu	−0.61

TABLE XXVI. (*Continued*).

State configuration	Calculated[a] A	a	Empirical Nucleus	a	Nucleus	a
			^{161}Ho	−0.66	^{171}Lu	−0.69
			^{163}Ho	−0.67	^{173}Lu	−0.76
			^{165}Ho	−0.46	^{175}Lu	−0.85
			^{161}Tm	−0.69		
			^{163}Tm	−0.71	^{177}Lu	−0.91
			^{165}Tm	−0.72	^{177}Ta	−0.79
			^{167}Tm	−0.72	^{179}Ta	−0.85
			^{169}Tm	−0.77	^{187}Re	−1.12
$1/2^-[541]$	154	+3.45	^{155}Tb	+1.86	^{173}Lu	+4.27
	164	+3.47	^{161}Tb	+2.42	^{175}Lu	+5.11
	178	+4.72	^{157}Ho	+1.89	^{177}Lu	+6.36
	186	+4.78	^{159}Ho	+2.11	^{171}Ta	+4.32
			^{161}Ho	+2.30	^{173}Ta	+4.76
			^{163}Ho	+2.55	^{175}Ta	+5.06
			^{165}Ho	+2.89	^{177}Ta	+5.54
			^{163}Tm	+2.20	^{179}Ta	+6.06
			^{165}Tm	+2.63	^{177}Re	+5.11
			^{167}Tm	+3.16	^{179}Re	+5.93
			^{169}Tm	+3.82	^{181}Re	+6.89
			^{171}Tm	+4.77	^{183}Re	+7.33
			^{169}Lu	+3.30	^{183}Ir	+4.82
			^{171}Lu	+3.90	^{185}Ir	+7.75
$1/2^+[420]$	154	+1.25	^{151}Pm	+1.22	^{157}Eu	+1.0
	164	+1.19	^{153}Pm	+1.35	^{159}Eu	+1.0
			^{153}Eu	+1.43	^{163}Tb	+0.96
			^{155}Eu	+2.14	^{163}Ho	+1.0
$1/2^+[400]$	154	+0.64	^{183}Re	0.40	^{187}Ir	0.06
	164	+0.42	^{185}Re	0.40	^{189}Ir	−0.01
	178	+1.27	^{187}Re	0.38	^{191}Ir	−0.03
	186	+0.45	^{185}Ir	0.02	^{193}Ir	−0.009
$1/2^-[550]$	154	−5.75	^{155}Eu	−1.11		

[a]The Nilsson parameters used for calculation are $\kappa_{\text{proton}}=0.0637$, $\mu_{\text{proton}}=0.6$, $\kappa_{\text{neutron}}=0.0637$, $\mu_{\text{neutron}}=0.42$ (for $A<175$); $\kappa_{\text{proton}}=0.0620$, $\mu_{\text{proton}}=0.614$, $\kappa_{\text{neutron}}=0.0636$, $\mu_{\text{neutron}}=0.393$ (for $A>175$). The deformation parameters used are $\epsilon_2=0.2$, $\epsilon_4=0.03$ (for $A=154$); $\epsilon_2=0.26$, $\epsilon_4=0.0$ (for $A=164$); $\epsilon_2=0.22$, $\epsilon_4=0.06$ (for $A=178$); $\epsilon_2=0.19$, $\epsilon_2=0.19$, $\epsilon_4=0.04$ (for $A=186$).

TABLE XXVII. Decoupling parameter values for $K=1/2$ states in odd-N rare-earth nuclei. In the second column A denotes the mass number.

State configuration	Calculated[a] A	a	Empirical Nucleus	a	Nucleus	a
$1/2^+[400]$	154	+0.05	^{151}Sm	−0.55	^{155}Gd	+0.23
	164	+0.18	^{153}Sm	+0.44	^{163}Dy	−0.026
	178	+0.13	^{155}Sm	+0.43	^{163}Er	+0.12
	186	+0.06				
$1/2^+[660]$	154	+6.63	^{159}Gd	+4.6		
	164	+6.56	^{165}Er	+3.12		
	178	+6.77				
	186	+6.81				
$1/2^-[530]$	154	+1.28	^{151}Nd	−0.30	^{159}Dy	+0.20
	164	+1.02	^{153}Sm	−0.05	^{163}Dy	−1.29
	178	+4.29	^{155}Gd	−0.47[b]	^{163}Er	+0.56
			^{157}Gd	(+0.25)	^{165}Er	+0.53
			^{157}Dy	+0.77		

TABLE XXVII. (*Continued*).

State configuration	Calculated[a] A	a	Empirical Nucleus	a	Nucleus	a
$1/2^-[510]$	154	−0.002	^{155}Gd	+0.11	^{175}Yb	+0.19
	164	−0.09	^{159}Gd	+0.34	^{177}Yb	+0.20
	178	+0.26	^{161}Gd	−0.18	^{177}Hf	(−0.44)
	186	+0.33	^{157}Dy	−0.12	^{179}Hf	+0.16
			^{159}Dy	−0.004	^{181}Hf	+0.18
			^{161}Dy	−0.05	^{179}W	−0.04
			^{163}Dy	+0.03	^{181}W	+0.59
			^{165}Dy	+0.05	^{183}W	+0.19
			^{163}Er	−0.36	^{185}W	+0.10
			^{165}Er	+0.06	^{187}W	0.00
			^{167}Er	+0.06	^{183}Os	+0.23
			^{169}Er	+0.06	^{185}Os	+0.02
			^{171}Er	−0.08	^{187}Os	+0.04
			^{171}Yb	0.00	^{189}Os	−0.17
			^{173}Yb	+0.22		
$1/2^+[651]$	154	+2.24	^{155}Gd	+1.14		
	164	+1.98	^{159}Gd	(−0.45)		
	178	+4.58	^{161}Gd	(−0.50)		
	186	+4.64	^{175}Yb	+3.29		
$1/2^-[521]$	154	+0.78	^{153}Sm	+0.33	^{173}Yb	+0.68
	164	+0.88	^{155}Sm	−0.21	^{175}Yb	+0.75
	178	+0.73	^{153}Gd	+0.79	^{171}Hf	+0.78
	186	+0.64	^{155}Gd	+0.35	^{173}Hf	+0.82
			^{157}Gd	(+0.22)	^{175}Hf	+0.75
			^{159}Gd	+0.46	^{177}Hf	+0.58
			^{161}Gd	+0.21	^{179}Hf	+0.66
			^{157}Dy	+0.43	^{173}W	+0.72
			^{159}Dy	+0.43	^{175}W	+0.79
			^{161}Dy	+0.44	^{177}W	+0.79
			^{163}Dy	+0.23	^{179}W	+0.82
			^{165}Dy	+0.58	^{181}W	+0.48
			^{163}Er	+0.47	^{183}W	+0.70
			^{165}Er	+0.56	^{185}W	+0.86
			^{167}Er	+0.70	^{177}Os	+0.79
			^{169}Er	+0.83	^{179}Os	+0.82
			^{167}Yb	+0.71	^{183}Os	+0.82
			^{169}Yb	+0.79	^{185}Os	+0.49
			^{171}Yb	+0.85	^{187}Os	+0.38

[a]Parameters used for calculation are given in Table XXVI.
[b]This value is derived (Sheline and Sood, 1989) using the 422-keV $1/2^-$ level in ^{155}Gd as the $K^\pi=1/2^-$ bandhead. The alternative choice of 451 keV $1/2^-$ level as this bandhead yields $a=-1.02$.

TABLE XXVIII. "Anomalous" values of empirical decoupling parameter in odd-N nuclei.

Nucleus	$1/2^-[510]$	$1/2^-[530]$	$1/2^+[651]$	$1/2^+[400]$	Comment
^{151}Nd		−0.30			Octupole?
^{151}Sm				−0.55	Transitional
^{153}Sm		−0.05			Octupole
^{155}Gd	+0.11	−0.46			Octupole
^{159}Gd	+0.34		−0.45		
^{161}Gd			−0.50		
^{157}Dy	−0.12				Octupole?
^{163}Dy		−1.29		−0.026	
^{163}Er	−0.36				
^{177}Hf	−0.44				
^{189}Os	−0.17				

modes of excitation bringing in the dominant contribution. Thus we list the 827-keV level in ^{161}Ho as $5/2^-[532]$ rather than $5/2^-\{7/2^-[523]_p, 5/2^-[523]_n, 3/2^-[521]_n\}$. We also do not include here the 860-keV level in ^{163}Tm, which was assigned the same 3qp configuration as the 827-keV level in ^{161}Ho. The 515-keV level in ^{165}Ho, not included here but listed in our Table V as the $3/2^-\{7/2^-[523]\otimes 2^+\}$ vibrational state, also has a small $\{7/2^-[523]_p, 7/2^+[413]_p, 3/2^+[411]_p\}$ 3qp component. The 884-keV level in ^{163}Dy is now assigned a vibrational configuration rather than the 3qp configuration $1/2^+\{3/2^+[411]_p, 7/2^-[523]_p, 5/2^-[523]_n\}$. Moreover, the earlier 3qp configuration $5/2^+\{7/2^-[514]_n, 9/2^-[514]_p, 7/2^+[404]_p\}$ suggested for the 905-keV level in ^{181}Hf and the 1125-keV level in ^{183}Hf has been reassigned as the one-quasiparticle configuration $7/2^-[514]$ because of the effect of hexadecapole deformation on the proton orbitals in Lu isotopes (see Sec. VI.A for a full discussion).

Soloviev (1963) calculated the energies of 3qp states and also suggested specific spin-flip beta transitions that may feed 3qp states of the (nnp) and (ppn) type. Schematic diagrams for such transitions are given in Fig. 14, and their role in identifying 3qp structures has been discussed by Meijer (1976) and more recently by Sood and Sheline (1989b). One must resort to other methods like Coulomb excitation or gamma deexcitation of highly excited large angular momentum states populated in the (HI,xn) reactions to populate (nnn)- or (ppp)-type 3qp states.

The characteristic features helpful in identifying 3qp states as summarized by Bunker and Reich (1971) are (1) a high-spin value unexplained by other kinds of excitations; (2) direct population of the state by a fast spin-flip beta transition, unexplained as a single-particle transition to either a one-quasiparticle or vibrational state; and (3) relatively strong population of the state by single-nucleon pickup/stripping on an odd-odd target. Sometimes empirical energy systematics of the 2qp excitations in neighboring even-even nuclei may provide an important clue in identifying the 3qp states formed by coupling the ground-state configuration of the odd-A system to the 2qp excitation of the neighboring even-even nucleus. For example, the 3qp states seen in odd-A Hf isotopes exhibit very similar energy systematics and rotational bands, as do their 2qp counterparts in the even-even Hf isotopes (Dracoulis and Walker, 1979). Since the 3qp states occur at relatively high excitation energies, considerable admixture with vibrational states is possible. Conclusive experimental identification of particularly the low angular momentum 3qp states is often difficult due to such admixtures.

A theoretical treatment of the 3qp states was presented by Pyatov and Chernyshev (1964) using a spin-dependent delta-force for the residual interaction between two of the three quasiparticles. Neiburg *et al.* (1972) used the same formalism to calculate the energy splitting of the 3qp multiplets. However, the agreement with the data available at that time was poor and inconclusive. The theoretical treatment of the 3qp states and their admixture with vibrational states therefore remains an open problem.

A few five-quasiparticle configurations assigned to some states are mentioned in the footnotes to the tables of 3qp states.

VI. SYSTEMATICS OF INTRINSIC STATES IN THE RARE-EARTH REGION

The systematics of the empirical data on one-quasiparticle energies in the odd-A deformed nuclei

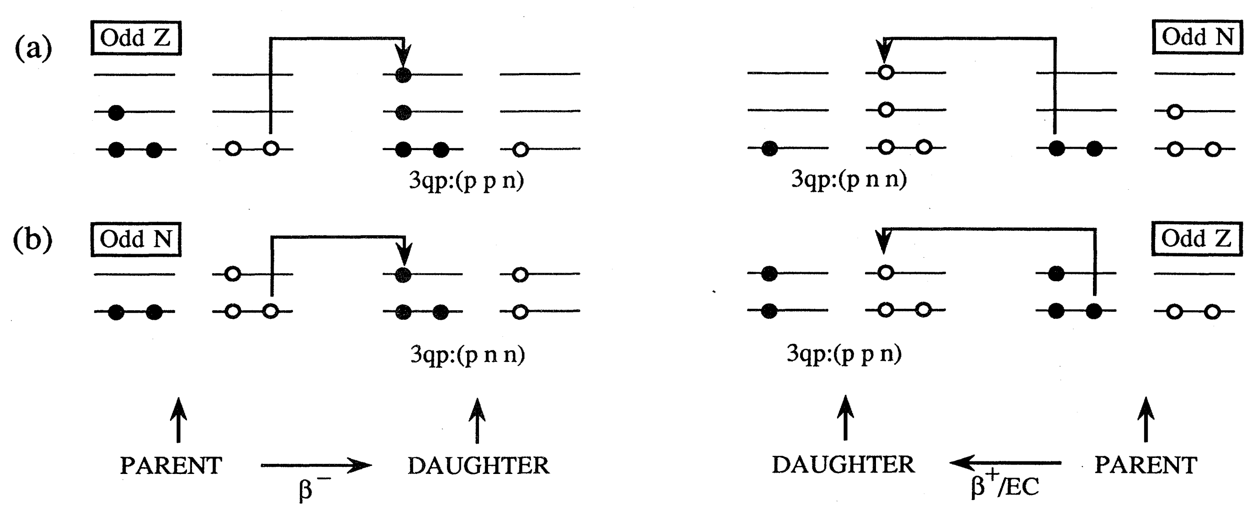

FIG. 14. Schematic beta decays of odd-A deformed nuclei showing spin-flip transitions populating 3qp states in the daughter nuclei: ●, protons; ○, neutrons. Fast beta transitions that are allowed unhindered (au) involve nucleons having the same asymptotic quantum numbers with the proton in the $\Omega=\Lambda+1/2$ state and the neutron in the $\Omega=\Lambda-1/2$ state. From Sood and Sheline (1989b).

within the mass range $151 \leq A \leq 193$ is presented in Figs. 15 and 16. We have included nuclei with $N \geq 88$ for the odd-Z case and $N \geq 89$ for the odd-N case.

The ground state of each nucleus is shown by a solid circle in the figures. The rest of the intrinsic excitations, classified as particle and hole excitations, are plotted above and below the ground state, respectively. It is to be remembered that such a classification is ambiguous for states lying close to the Fermi surface due to the pairing correlations and/or incomplete guidance from the particle transfer reactions.

The intrinsic states in most of the cases represent the lowest-lying level of the rotational band having $I=K$. For a few $K=\frac{1}{2}$ bands or strongly-Coriolis-perturbed bands, however, the lowest-lying level may have $I \neq K$; the angular momentum $(2I)$ is then indicated in the figures. In a few cases, the bandhead is not experimentally observed; the extrapolated value of the bandhead is then plotted and such points are enclosed in parentheses in the figures. In addition, a vibrational admixed state shown in the figures is labeled with the symbol V.

A. One-quasiproton states

1. $N=88$ isotopes and the collapse of Nilsson orbitals

The $N=88$ nuclei lie in the transition region and are nearly spherical in shape. However, a number of experimental features point to the coexistence of spherical and deformed shapes in nuclei of this region. Three $N=88$ isotones, namely ^{151}Eu, ^{153}Tb, and ^{155}Ho, are known to exhibit well-developed positive- and negative-parity rotational bands. Furthermore, in ^{149}Pm, ^{151}Eu, and ^{153}Tb, the lowest $7/2^-$ state, populated with appreciable intensity in single-proton stripping reactions, is observed to lie 30–50 keV above the first $11/2^-$ state (Straume, Løvhøiden, and Burke, 1976). Whereas the observed $11/2^-$ can be identified with the $h_{11/2}$ shell-model orbital, the presence of the $7/2^-$ state requires consideration of deformed orbitals. The calculations performed by Alikov *et al.* (1978) for a series of Tb isotopes ($N=84$ to 92) give a small prolate deformation for $N=88$, a small oblate shape for $N=86$, and a spherical shape for $N=84$ Tb isotopes.

Two facts are clear from Fig. 15(a). First, the three $N=88$ nuclei—^{151}Eu, ^{153}Tb, and ^{155}Ho—all have a ground-state assignment $K^{\pi}=5/2^+$, identified as the $5/2^+[402]$ orbital, which is different from the ground-state assignments in other Eu, Tb, and Ho isotopes. This implies that these $N=88$ nuclei fall in a region of sudden shape changes. Secondly, all the 1qp excitations seem to be converging in the $N=88$ region. The $5/2^+[402]$, $3/2^+[411]$, and $1/2^+[420]$ orbitals belonging to the $d_{5/2}$ shell-model orbit are seen to approach each other rather quickly with a decrease in the neutron number in a given isotopic chain. The $7/2^+[404]$ and $5/2^+[413]$ orbitals, arising from the $g_{7/2}$ shell-model orbit, also exhibit similar behavior. This trend suggests that we are observing the collapse of the Nilsson orbitals toward shell-model orbits with decreasing deformation.

From a different point of view, we can see that the 1qp states fan out in a manner very similar to the levels in a Nilsson diagram as we go from a lower neutron number to a higher neutron number in any given isotopic chain consistent with the increasing deformation. This general trend is, however, seen to reverse itself around $Z=72$, where an increase in neutron number leads to a decrease in nuclear deformation, and the 1qp states begin to collapse towards each other again.

2. Proton gaps and the crossing of single-particle levels

Two of the important qualitative tests of nuclear models are their ability to predict correctly the position of gaps in the level scheme and their ability to reproduce the crossings of the empirical 1qp levels in energy and deformation. The gaps are known to play an important role in influencing many nuclear properties such as stability, high-spin behavior, pairing, etc. (Brack *et al.*, 1972; Jain, 1975; Jain and Sood, 1978). The crossings represent crucial identification marks on a Nilsson diagram. As we shall show, the Nilsson diagram for single-proton states shown in Fig. 5, which considers the effects of quadrupole and hexadecapole deformation, satisfies both these conditions reasonably well.

We shall discuss the gaps first. A prominant gap in the empirical systematics is seen below the $5/2^-[532]$ orbital and above the $3/2^-[541]$ orbital in the $Z=61$ to 65 isotopic chains in Fig. 15(a). This probably corresponds to the gap seen at the 60th proton in Fig. 5. The next prominant gap is seen in the empirical data for the $Z=65$ isotopic chain, where the $3/2^+[411]$ orbital is the ground state [Fig. 15(a)]. This corresponds to the gap in the single-particle-level scheme at the 66th proton, between the $3/2^+[411]$ and $7/2^-[523]$ orbitals. However, the $Z=66$ gap seems considerably diminished in the empirical data as we go to the $Z=67$ and 69 isotopic chains. Instead, the empirical data exhibit the development of a new gap just below the $3/2^+[411]$ orbital; such a development is absent in the theoretical single-particle diagram. The next important gap is seen for the 76th proton in the calculated results (Fig. 5). A large gap exists for $Z=75$ Re isotopes just above the $5/2^+[402]$ ground state. However, the empirical gap lies between the $5/2^+[402]$ and $3/2^+[402]$ orbitals and not between the $9/2^-[514]$ and $11/2^-[505]$ orbitals, as seen in the calculated scheme. It therefore appears that a minor rearrangement of the levels is required. This reversal in the ordering of the $9/2^-[514]$ and $5/2^+[402]$ proton orbitals is seen to occur for the $Z=73$ Ta isotopes and is probably the result of decreasing quadrupole and increasing hexadecapole deformation; the $9/2^-[514]$ orbital goes down in energy and $5/2^+[402]$ comes up at the gap,

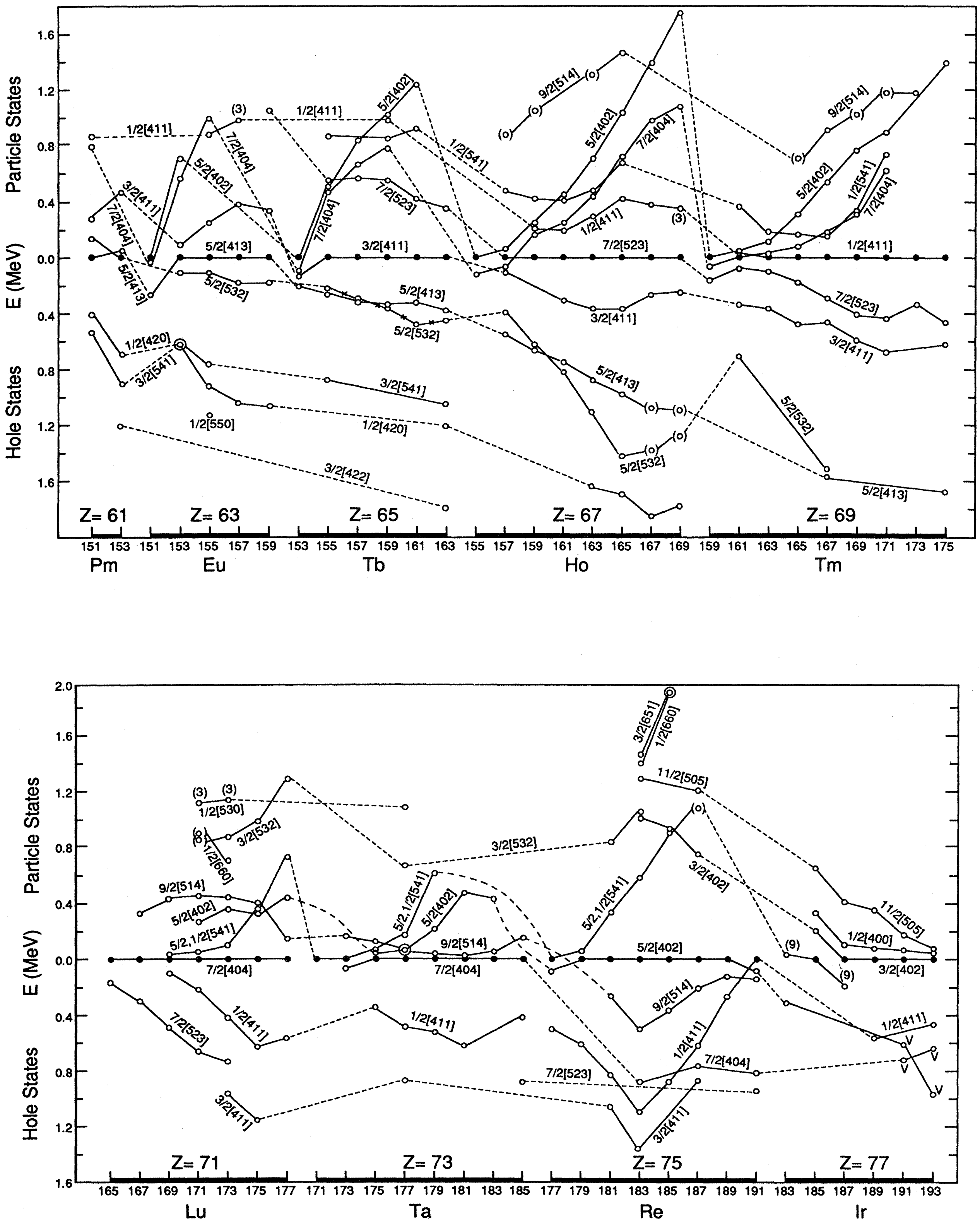

FIG. 15. Experimental single-proton energy systematics for the rare-earth isotopes having (a) $Z=61$ through $Z=69$ and (b) $Z=71$ through $Z=77$: ●, ground states. Predominantly particle and hole states are plotted, respectively, above and below the ground state. For detailed discussion see Sec. VI.

as shown in the extreme right-hand side of Fig. 5. An important effect of the presence of a gap in the single-particle-level scheme is that most of the particle excitations above the gap (if the gap is on the side of the particle excitations), or most of the hole excitations below the gap (if the gap is on the side of hole excitations), are more difficult to observe because they have moved significantly farther from the Fermi surface. However, a word of caution is in order here. The experimental data correspond to the quasiparticle energies, not to the single-particle energies. Unless a model-independent way (e.g., particle transfer reaction studies) is available to put the states

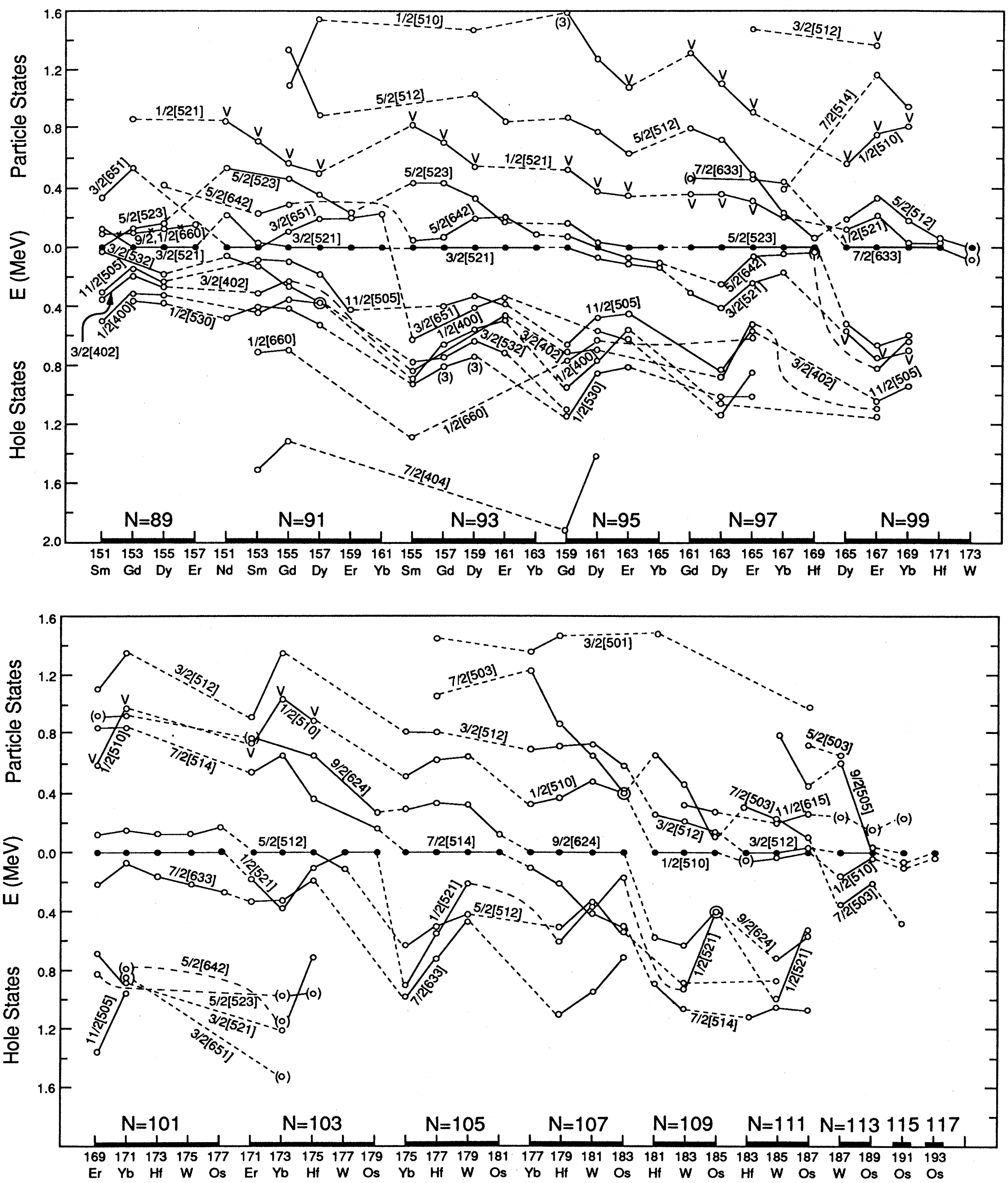

FIG. 16. Experimental single-neutron energy systematics for rare-earth isotones having (a) $N=89$ through $N=99$ and (b) $N=101$ through $N=117$. States having some vibrational component are labeled by the symbol V.

above or below the Fermi surface, the above argument is somewhat circular; in such a case, crossings, rather than gaps, are the more meaningful feature.

We shall now discuss the crossings of the single-particle states. We find that the crossings of the empirical 1qp states are mostly well reproduced by the calculated single-particle states, provided we take the proper variation in ϵ_2 and ϵ_4 into account. We illustrate this by taking two specific examples: the Ho isotopic chain and the Re isotopic chain.

a. Ho isotopes

In order to compare the energy systematics of 1qp states with that predicted by the Nilsson model, one must convert the empirical quasiparticle energies into empirical single-particle-level energies (Ogle *et al.*, 1971; Chasman *et al.*, 1977). Energy corrections due to pairing correlations, vibrational admixture, and zero-point rotational energy are required. The most important of these is the pairing correction. The empirical single-particle energies so obtained may then be compared directly with the theoretical single-particle energies.

We have, however, adopted a much simpler method that helps in comparing in an approximate manner the energy systematics from the Nilsson model with the empirical energy systematics. In Fig. 17, we show such a comparison for a chain of Ho isotopes from $A=155$ to 169. The theoretical systematics were obtained by taking into account three factors. First, the deformation was varied from isotope to isotope as predicted by the calculations of Bengtsson *et al.* (1986). Second, Nilsson-model calculations were performed for each of these deformations using the potential parameters κ and μ (Eq. 3.10) of MHO from Nilsson *et al.* (1969). Theoretical single-particle energies were obtained by setting the empirically known ground state to zero energy (Fermi level) and treating the rest of the states as particle/hole states depending on whether they lay above or below the Fermi level. Finally, the calculated particle/hole energies were then halved to take into account the effect of pairing

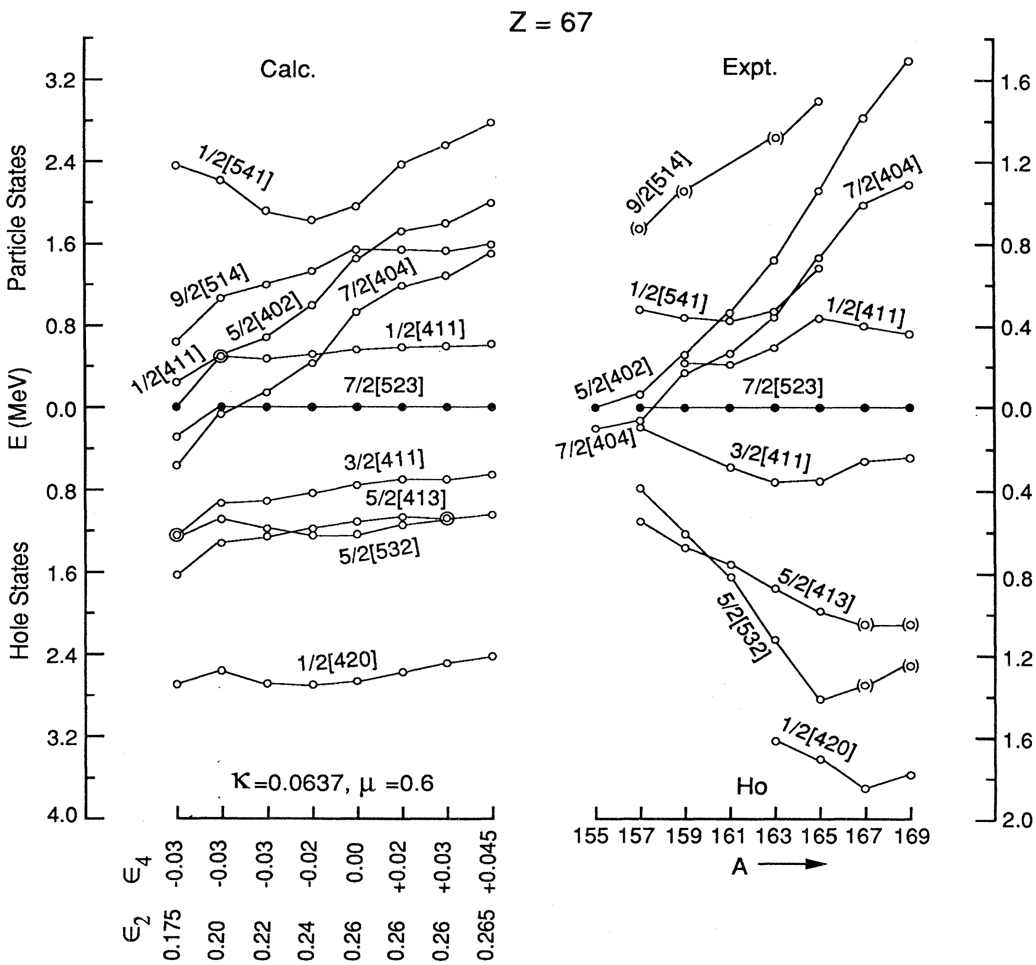

FIG. 17. Comparison of the experimental single-proton energy systematics for the $Z=67$ isotopes with the calculated systematics obtained from the Nilsson model (MHO).

correlations in an approximate way (Bunker and Reich, 1971). The reduction of calculated energies by a factor of 2 was achieved on Fig. 17 itself by introducing a factor of 2 in the scales.

We note that all the qualitative features, including the crossings of levels and their relative positions, compare very well with the empirical data. The only major discrepancy is in the location of the $1/2^-[541]$ orbital.

The empirical excitation energies of the $1/2^-[541]$ state are much smaller than those predicted by calculations, though the general trend is similar. The $1/2^-[541]$ orbital comes down after crossing the $Z=82$ gap with a steep slope, indicative of a deformation driving nature; i.e., the lower this orbital is observed, the more deformed the nucleus. Therefore lower excitation energy would occur if greater deformation were assigned to this state. In any case, the energy of the state is very sensitive to deformation.

We note that the $1/2^-[541]$ orbital rarely becomes the ground state in nuclei near the line of β stability. It is observed as the nuclear ground state in ^{171,173}Ta, ^{177}Re, and ^{185}Ir, which are all neutron-deficient nuclei at the beginning of their respective isotopic chains.

The Nilsson model predicts a value of ≈ 3.5 to 4.8 for the decoupling parameter of the $1/2^-[541]$ orbital, while the observed values range from 2.0 to 8.0 (see Table XXVI). In Fig. 18 we show the variation of the empirical a values of the $1/2^-[541]$ band for different groups of isotopes. It is interesting to note that the decoupling parameter values rapidly increase as we go from lighter to heavier nuclei or as the $1/2^-[541]$ band approaches the Fermi level. This large variation in the value of a remains unexplained by the Nilsson model. The Woods-Saxon potential seems to give a better description of this orbital (Bengtsson *et al.,* 1989).

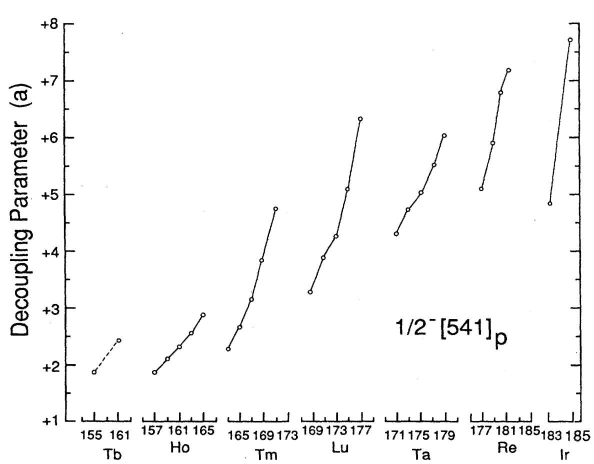

FIG. 18. Empirical decoupling parameter values for bands based on the $1/2^-[541]$ proton orbital taken from Table XXVI. The Nilsson-model values lie in the range of $a \approx 3.5$ to 4.8.

b. Re isotopes

In Fig. 19 we present a plot for the Re isotopes, which is similar to Fig. 17 for the Ho isotopes. It is encouraging to note that our approximate calculations generally reproduce the ordering of the levels and their crossings as observed in the empirical systematics. The change in the slope of the empirical hole-state systematics, seen at $A=183$, is also present in the calculated systematics. The $1/2^+[400]$ orbital, which is seen to lie above the $3/2^+[402]$ orbital in the calculations, is observed experimentally to lie below the $3/2^+[402]$ orbital, basically because of the vibrational admixture. The empirical excitation of the $11/2^-[505]$ orbital is, however, seen to be higher than that predicted by the Nilsson model.

3. Decoupling parameters in the $1/2^+[411]$ orbital

The systematics of the decoupling parameter values of the $1/2^+[411]$ orbital is shown in Fig. 20. The shaded region represents the range of values predicted by the Nilsson model. The decoupling parameters of ^{151}Pm and ^{165}Ho are particularly low. A γ-vibrational admixture of $\{5/2^+[413]\otimes 2^+\}$ in the former and $\{3/2^+[411]\otimes 2^+\}$ in the latter nuclide can explain these low values, since the vibrational component has a zero decoupling parameter. An octupole shape effect is also expected in ^{151}Pm. Furthermore, the very large value of a in ^{155}Eu is most probably explained by octupole deformation. However, the variation of a in the Ho isotopic chain is totally different from that in the Tm, Lu, and Ta isotopic chains. This is probably because of large Coriolis mixing between the $1/2^+[411]$ and the $3/2^+[411]$ orbitals in the Ho isotopes, as is evidenced by a stronger odd-even staggering effect in the Ho isotopes when compared to other nuclei.

4. Hexadecapole deformation

The hexadecapole deformation is important to reproduce the level orderings and spacings as illustrated below for the neutron-rich Lu isotopes. In Fig. 21 we show the calculated energy difference between the $9/2^-[514]$ and the $7/2^+[404]$ proton orbitals for the Lu region as a function of the hexadecapole deformation parameter ϵ_4 for three different values of the quadrupole deformation parameter ϵ_2. The energy difference becomes negative for an increasing ϵ_4 deformation because of a crossover of the two orbitals. We see from Fig. 21 that the crossover occurs just below $\epsilon_4=0.06$ for $\epsilon_2=0.28$. It is therefore expected that the $9/2^-[514]$ orbital will become or be very near the ground state for ^{179}Lu as a result of increasing ϵ_4. The empirical systematics for the $9/2^-[514]$ proton orbital shown separately in Fig. 22 clearly confirms this effect; an extrapolation of the energy difference plotted in the figure puts the $9/2^-[514]$ orbital at a lower energy than the $7/2^+[404]$ orbital around the $N=108$ Lu isotope.

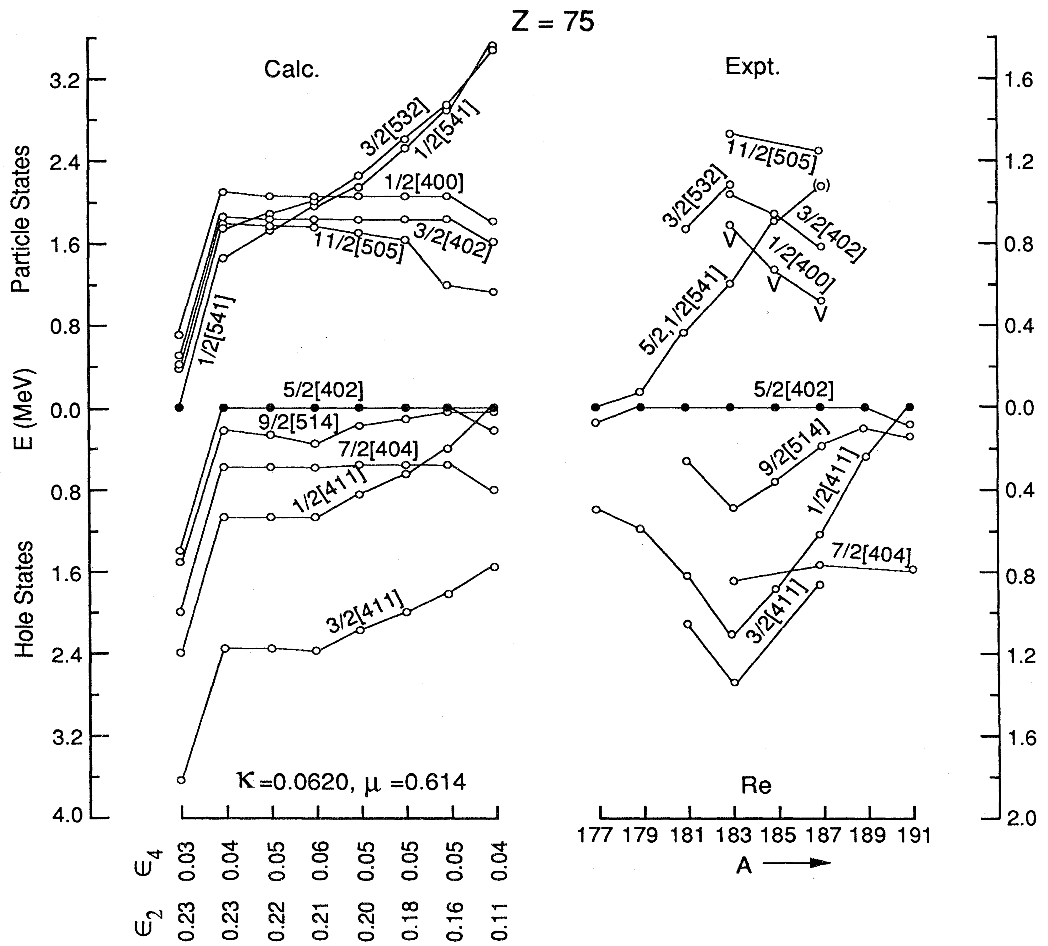

FIG. 19. Comparison of the experimental single-proton energy systematics for $Z=75$ isotopes with the calculated systematics obtained from the Nilsson model (MHO).

5. The transitional Ir nuclei

In the W-Os-Pt region we observe a gradual transition from prolate to oblate shape with increasing neutron number and hence the presence of γ-asymmetric or triaxial shapes. The pairing-plus-quadrupole model of Kumar and Baranger (1968) indeed predicted a prolate-oblate

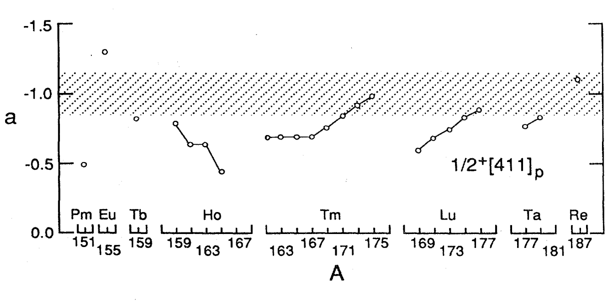

FIG. 20. Empirical decoupling parameter values for $1/2^{+}[411]$ proton bands. The shaded region indicates the range of values expected from the Nilsson model.

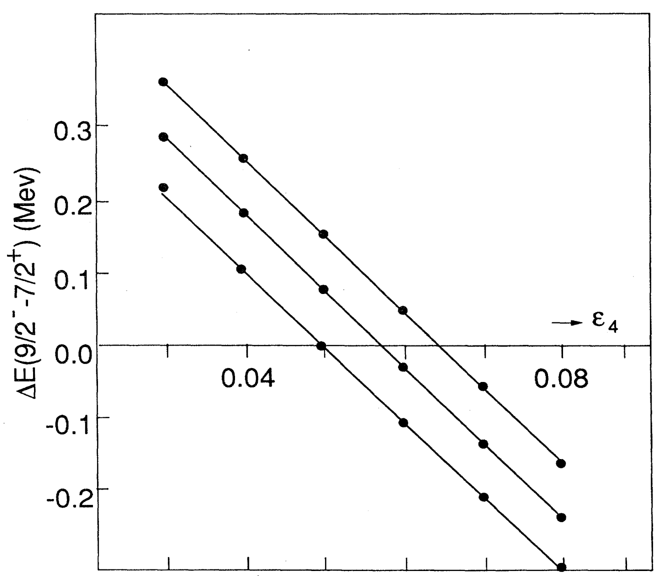

FIG. 21. Calculated energy difference between the $9/2^{-}[514]$ and $7/2^{+}[404]$ proton orbitals in the Lu ($Z=71$) region vs ϵ_4 for three values of ϵ_2.

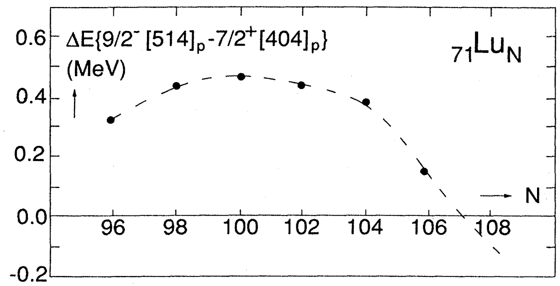

FIG. 22. Experimental energy difference between the $9/2^{-}[514]$ and $7/2^{+}[404]$ proton orbitals of the odd-A Lu isotopes vs the neutron number. A smooth extrapolation towards large N indicates a reversal in the sign of the energy difference at $N=108$.

shape transition in the Os-Pt region with shallow minima in the potential-energy surfaces implying nuclei that are soft towards γ vibrations.

A successful interpretation of $^{187-193}$Ir positive-parity states was given by Vieu *et al.* (1979) in terms of a particle-plus-asymmetric-rotor model. McGowan *et al.* (1986, 1987) also used a triaxial rotor model with large $\gamma(\sim 24°)$ deformation to successfully describe the level energies and E2 transitions of ^{191}Ir and ^{193}Ir.

If we consider individual nuclei, it is interesting to note that the $1/2^{-}[541]$ band is the ground state for both ^{183}Ir and ^{185}Ir. In both cases the band structure is quite anomalous because of the very large decoupling parameters ($a\sim 7.6$). As we move to heavier Ir isotopes, the $3/2^{+}[402]$ state is seen to become the ground state, and the $1/2^{+}[400]$ state is the first excited state. These features may be qualitatively explained if we assume a vanishing ϵ_4 deformation and a very small ϵ_2 deformation. It becomes evident from the γ dependence of the single-particle levels shown in Larsson (1973) that the $3/2^{+}[402]$ orbital crosses over the $1/2^{-}[541]$ and $11/2^{-}[505]$ orbitals to become the ground state for $Z=77$ in the heavier Ir isotopes. Some γ deformation is therefore definitely present. We note that the asymptotic quantum number designations are not strictly valid for axially asymmetric shapes, and that K is not a good quantum number because of the mixing introduced by γ deformation. It is, however, clear that a more complete experimental and theoretical understanding of the transitional Ir isotopes stands as a challenge to both experimentalists and theorists.

B. One-quasineutron states

The empirical energy systematics of one-quasineutron states is displayed in Figs. 16(a) and 16(b). A proper understanding of these systematics requires the knowledge of a nucleus-to-nucleus variation in deformation. Some general remarks can be made. We observe that the one-quasineutron states are clustered together for the $N=89$ isotones, but begin to spread out as the neutron number and the deformation increase. This spreading out, however, reaches a limit at about $N=101$, and a compression sets in at about $N=103$ as the deformation reverses its trend and starts decreasing. These experimental trends represent the increased energy splitting of the orbitals degenerate in the shell-model limit at the beginning of the region of deformation and the tendency toward collapse with the approach of the next closed shell.

1. $N=89$ isotones

The $N=89$ nuclides—^{151}Sm, ^{153}Gd, ^{155}Dy, and ^{157}Er—lie at the limit of the stable deformation region. It is now understood that these transitional nuclei have a somewhat smaller, but definite, quadrupole deformation. Calculations based on the particle-rotor model are found to describe the level structure and other properties of the $N=89$ isotones quite satisfactorily (Katajanheimo and Hammarén, 1979; Alikov *et al.*, 1980).

The ground state of ^{151}Sm is observed to be the $5/2^{-}[523]$ state. This state then crosses over the $3/2^{-}[521]$ state to become a particle excitation, and the $3/2^{-}[521]$ state becomes the ground state of other $N=89$ nuclei. This crossing can be seen in the Nilsson diagram (Fig. 6) for neutrons at a deformation of $\epsilon_2=0.12$. Furthermore, the $5/2^{-}[523]$ state again crosses over the $1/2^{+}[660]$ state for ^{153}Gd, which is also reflected in the Nilsson diagram.

As we go from ^{151}Sm towards ^{155}Dy, the deformation decreases and all the single-neutron states converge towards the more degenerate shell-model states.

2. $N=91$ isotones

The deformation is expected to be larger in the $N=91$ isotones—greatest for ^{151}Nd and ^{153}Sm and decreasing slowly as we add more protons. The $3/2^{+}[651]$ state is the ground state for ^{151}Nd and ^{153}Sm, which then crosses the $3/2^{-}[521]$ state to become a particle excitation; the $3/2^{-}[521]$ state becomes the ground state for the rest of the $N=91$ isotones. The crossing of $3/2^{-}[521]$ and $3/2^{+}[651]$ states is reproduced by the Nilsson diagram shown in Fig. 6. The $5/2^{-}[523]$ state is approaching the $3/2^{+}[651]$ state at ^{159}Er; this feature is again reproduced by the Nilsson model.

3. Neutron gaps in the single-particle states

The first gap in the calculated single-particle-level scheme is seen to occur at $N=90$ for a deformation $\epsilon\approx 0.3$. This gap is clearly visible in the empirical systematics of single-quasineutron states for the $N=91$ to 97 isotones. A major gap is next observed at $N=98$, which persists in the empirical systematics for $N=99$ to 103 isotones and is reproduced by the Nilsson diagram. The gap at $N=98$ is very prominent, so that it becomes very difficult to excite the hole excitations beyond this gap. A relatively smaller gap occurs at $N=104$ in the calculated single-particle scheme and is seen briefly in the empirical systematics for the $N=101$ and 103 isotones. Finally, a major gap is again observed in the Nilsson diagram at $N=108$, which is the gap seen in the empirical systematics from $N=107$ onwards. The $N=108$ gap again results in a decreased number of excitations beyond the gap.

4. Comparison of the empirical and calculated systematics

We compare the empirical energy systematics with the calculated systematics for two cases: $N=97$ and $N=105$ isotones shown in Fig. 23 and Fig. 24, respectively. The calculated energy systematics was obtained by following the method outlined in Sec. VI.A for the one-quasiproton-state systematics.

The systematics from the calculated level energies compares very well with the empirical systematics for both cases. The ordering of the levels and their behavior are properly reproduced by the Nilsson model. The only discrepancy occurs for the $N=97$ isotones, where the empirical excitation energies of $1/2^-[510]$ and $1/2^-[521]$ states are lower than those calculated. As documented in Table XV, both of these states are calculated to have some vibrational admixture, which probably is responsible for the energy lowering.

5. $1/2^-[521]$ state

The $1/2^-[521]$ neutron state has now been seen in most of the odd-N nuclei and occurs as the ground state in the $N=101$ isotones. There are indications that this state has a small γ-vibrational admixture for $A=153$ to 163 nuclei. The γ-vibrational states based on both $3/2^-[521]$ and $5/2^-[523]$ base states can contribute. The decoupling parameter values for all the odd-N $K=1/2$ bands are summarized in Table XXVII. We find

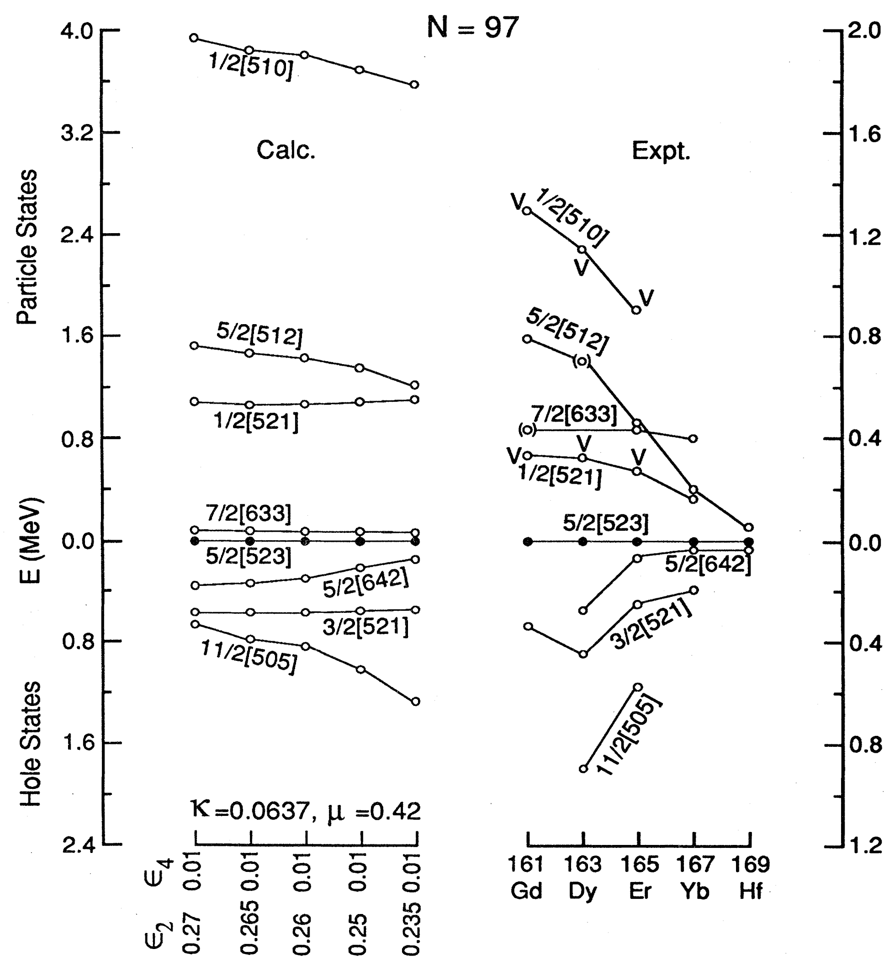

FIG. 23. Comparison of the empirical single-neutron energy systematics of $N=97$ isotones with the calculated systematics obtained from the Nilsson-model (MHO) calculations.

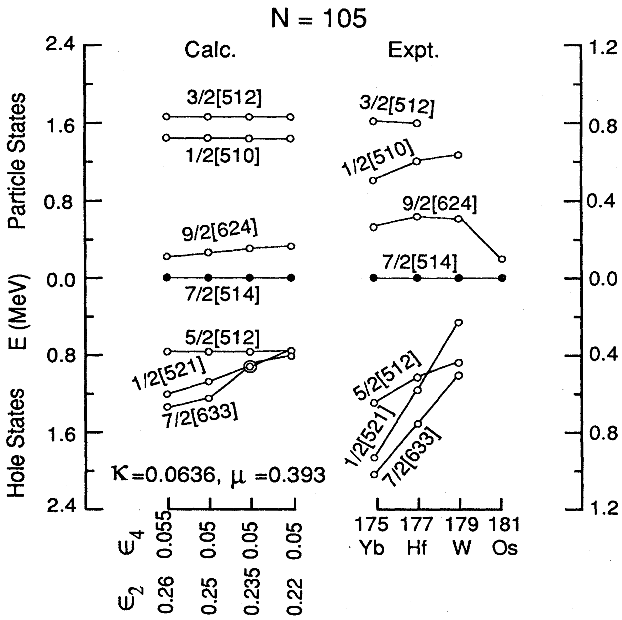

FIG. 24. Comparison of the empirical single-neutron energy systematics of $N=105$ isotones with the calculated systematics obtained from the Nilsson-model (MHO) calculations.

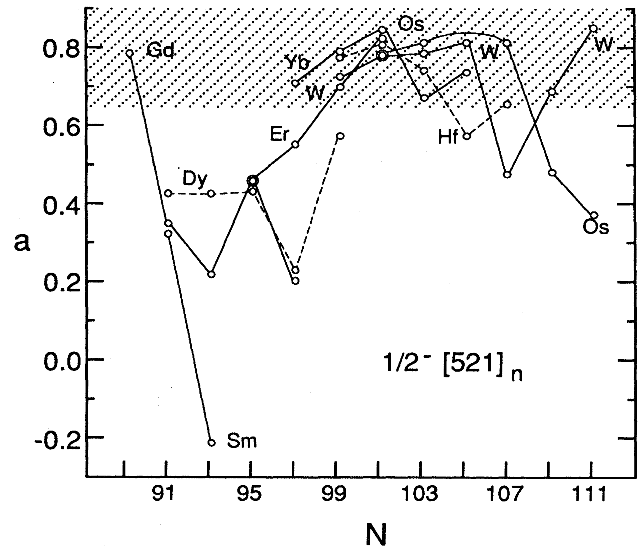

FIG. 25. Systematics of the empirical decoupling parameter values of the $1/2^-[521]$ neutron orbital vs the neutron number N. The shaded region indicates the range of values expected from the Nilsson-model calculations.

that the decoupling parameter values for Sm, Gd, Dy, and ^{163,165}Er are smaller than those predicted by the Nilsson model, except for the cases of ^{155}Sm, which has a negative value, and ^{153}Gd, which has $a=0.79$. The calculations of Katajanheimo and Hammarén (1979) based on the Woods-Saxon potential, however, give the value $a=0.41$, which seems to be consistent with the decoupling parameter value in the mass range $A=153$ to 163. These particle-rotor calculations therefore support a pure single-particle interpretation for the $1/2^-[521]$ band. However, the decoupling parameter for the mass range $A=153$ to 163 is 50% lower than for the higher masses, as shown in Fig. 25, where the shaded region reflects the range of values expected from the Nilsson model. Therefore some vibrational admixture appears probable.

An interesting feature seen in the systematics of the $1/2^-[521]$ decoupling parameter corresponds to a sudden dip in the value of a seen for $Z=70$ to 76 nuclei; more specifically, it occurs for $_{70}Yb_{103}$, $_{72}Hf_{105}$, $_{74}W_{107}$, and $_{76}Os_{109}$, with successively increasing Z and N values. The deformation systematics reveals that these nuclei probably represent the turning points where the nuclear deformation starts to decrease. This in turn may explain the decrease in the decoupling parameter values.

6. Anomalous decoupling parameters

Several $K=1/2$ states in lighter rare earths are found to have decoupling parameter values that considerably deviate from the general trends and the Nilsson-model predictions. Two specific cases for $1/2^+[411]_p$ and $1/2^-[521]_n$ have been presented, respectively, in Figs. 20 and 25, and also discussed earlier in the text. We have summarized the other odd-N cases in Table XXVIII. At least one is an $N=89$ nucleus (^{151}Sm) lying in the transitional region where octupole correlations are probable. Either its transition nature or octupole correlations may be invoked to try to explain the anomalous value of the $1/2^+[400]$ decoupling parameter. Four other nuclei are $N=91$ isotones—namely ^{151}Nd, ^{153}Sm, ^{155}Gd, and ^{157}Dy—and are expected to have octupole correlations that correlate with the anomalous decoupling parameters. A detailed discussion of these nuclei is presented later. It is, however, not clear why the decoupling parameters of the rest of the nuclei listed in Table XXVIII are so different from their normal values.

7. Positive-parity states

The $i_{13/2}$ neutron subshell gives rise to $1/2^+[660]$, $3/2^+[651]$, $5/2^+[642]$, $7/2^+[633]$, $9/2^+[624]$, $11/2^+[615]$, and $13/2^+[606]$ positive-parity states in the rare-earth region. The $1/2^+[400]$ and $3/2^+[402]$ states originating from the $N=4$, $d_{3/2}$ orbital come up and cross the $1/2^+[660]$ and $3/2^+[651]$ states around $\epsilon_2=0.26$. The only other positive-parity state seen in this mass region is the $1/2^+[651]$, which is too far away energetically to mix with the other positive-parity states.

A $\Delta N=2$ mixing between the $\{1/2^+[660], 1/2^+[400]\}$ and $\{3/2^+[651], 3/2^+[402]\}$ pairs of orbitals is expected because of their close proximity at deformations $\epsilon_2 \approx 0.26 \pm 0.02$. There are several experimental factors that clearly help distinguish between the states of the $i_{13/2}$ and the $d_{3/2}$ orbitals, such as the strong population of the $d_{3/2}$ states in single-nucleon transfer reactions and the very large positive decoupling parameter of the $1/2^+[660]$ band ($a \approx 6$) as compared to the $1/2^+[400]$ band ($a \approx 0.4$). The behavior of the rotational bands built on these states is therefore an important clue to the identity of these states. The $i_{13/2}$ bands have a very large Coriolis interaction between them. Therefore the rotational bands built on these states are expected to be highly distorted, and the resulting wave functions are highly mixed. The labeling of these states is therefore necessarily based on the major component expected to be present in the wave function.

8. Effect of hexadecapole deformation

The ϵ_4 deformation also affects the $\Delta N = 2$ mixing between the pairs of levels $1/2^+[400]$, $1/2^+[660]$, and $3/2^+[402]$, $3/2^+[651]$. It was observed by Mukherjee and Ramkrishna (1971) that the large empirical splitting of the two $3/2^+$ levels can be accounted for by a negative $r^2 Y_{40}$ term in the Nilsson Hamiltonian. We know that the ϵ_4 deformation is negative for the *Gd-Dy* region where $\Delta N = 2$ mixing has been observed. Furthermore, significant mixing is observed over a broader range of ϵ_2 values due to the ϵ_4 term, accounting for the observed $\Delta N = 2$ mixing in a large group of nuclei. However, some ambiguity still exists in classifying these states, because sufficient experimental data are not available. In particular, we consider the $3/2^+[402]$ and the $3/2^+[651]$ assignments made in $N = 97$ nuclei as ambiguous. The systematics in these cases suggests that the lower-lying excitation should be the $3/2^+[651]$ state, but the assignments taken from the literature indicate the opposite.

9. W and Os nuclei

The properties of odd-A Os and some W nuclei begin to deviate considerably from the predictions of the axially symmetric Nilsson model. There are two main reasons for this: First, the nuclear deformation is decreasing and therefore an increased Coriolis interaction is expected. Secondly, the character of nuclear deformation also undergoes a change from prolate symmetric to asymmetric or triaxial.

The ϵ_4 deformation is expected to reach its peak value in the Hf and W isotopes; it probably remains large for the lighter Os isotopes also. The $1/2^-[510]$ orbital is lowered by large ϵ_4 deformation and becomes the ground state for $N = 109$ isotones. At $N = 111$ the $3/2^-[512]$ orbital is expected to become the ground state. Experimentally we do observe the $3/2^-[512]$ configuration as the ground state in ^{183}Hf and ^{185}W. However, the $1/2^-[510]$ state is the ground state for ^{187}Os. This change in ground-state configuration for $N = 111$ nuclei may be explained as an effect of decreasing quadrupole deformation and increasing γ deformation.

For the four $N \geq 113$ nuclei shown in the systematics, only ^{191}Os has the ground state assigned as $9/2^-[505]$, while the other three ground states are assigned the $3/2^-[512]$ configuration. The experimental data on the (d,p) and (d,t) reactions indicate that the $7/2^-[503]$ configuration is a hole state in these nuclei, while no definite particle-hole character could be assigned to the $11/2^+[615]$ state (Benson *et al.*, 1977, 1978). This systematics may be understood within the Nilsson model by assuming a decrease in the ϵ_2 and ϵ_4 deformation for $N \geq 113$. Under these circumstances the $3/2^-[512]$ configuration becomes the ground state and the $7/2^-[503]$ configuration appears as a hole state. Since the $9/2^-[505]$ orbital crosses the $3/2^-[512]$ orbital at small deformation, it may also sometimes become the ground state.

In spite of the fact that we can manage to explain the ordering of the levels in $N \geq 109$ nuclei in the framework of the Nilsson model, a number of experimental facts remain to be explained. For example, one would expect that the 3/2 and 5/2 members of both the $1/2^-[510]$ and the $3/2^-[512]$ bands should be populated in the (d,p), (d,t) reactions, but the strengths of the four expected states are combined into only two by Coriolis coupling. This would suggest that the observed 5/2 state should have at most the sum of the unperturbed 5/2 strengths calculated for the two bands; similarly, the observed 3/2 state should have a strength that is not greater than the calculated 3/2 states summed value. However, for ^{189}Os and ^{191}Os, the observed transfer strengths are larger than the predicted sum (Benson *et al.*, 1977, 1978). Similar behavior in cross sections has been noticed in ^{185}W, but not in lighter W isotopes and not in ^{187}Os. The spectroscopic strengths calculated with Coriolis mixing of all the $5/2^-$ and $3/2^-$ states in this shell show that the lowest $5/2^-$ level receives the total $f_{5/2}$ strength while the second lowest $3/2^-$ state receives most of the $p_{3/2}$ strength.

These experimental observations indicate that the increasing dominance of the Coriolis interaction with decreasing deformation counteracts the fragmentation of transfer strengths caused by the deformation of the nuclear potential, thus tending to restore the cross-section pattern expected for a spherical nucleus.

C. Possible octupole-quadrupole deformation in the rare earths

As mentioned in Sec. II.A the $f_{7/2}$ and $i_{13/2}$ neutron orbitals and the $d_{5/2}$ and $h_{11/2}$ proton orbitals just beyond the double closed shell at ^{132}Sn are quite close together and near the Fermi surface. We therefore might expect these orbitals to give rise to low-lying $J^\pi = 3^-$ states, which may form the microscopic basis for octupole deformation in the neutron-excess rare-earth and near rare-earth regions. Indeed, Leander *et al.* (1982) have shown that the contour surface for the experimental 3^- states in even-even nuclei reaches a minimum in the $Z\sim56$ and $N=88-90$ region. Theoretical calculations of Nazarewicz, Olanders, Ragnarsson, Dudek, Leander, Möller, and Ruchowska (1984) have shown the existence of octupole shape minima in this same region, and Leander *et al.* (1985) have demonstrated a theoretical underbinding in these nuclei, which can be corrected by octupole deformations of the order of $\beta_3\sim0.10$.

Experimentally the spectroscopic study of octupole deformation in the rare earths has barely begun. Interlaced $K^\pi=0^+$ and 0^- bands at spins above $\sim8^+$ expected for octupole deformed even-even nuclei have been observed in ^{144,146}Ba, ^{146,148}Nd, and ^{150}Sm. Furthermore, many of the spectroscopic features, which identify octupole deformed odd-A nuclei outlined in Sec. III.A.3, have been observed in some of the odd-A rare-earth nuclei. These include ^{153}Sm and ^{155}Gd (Sheline and Sood, 1989), ^{151}Pm (Sood and Sheline, 1989a), and ^{153}Eu and ^{155}Eu (Sheline and Sood, 1990a). It can reasonably be expected that a number of other odd-A nuclei in this mass region may also have some of the features expected of octupole deformed nuclei.

Two sets of single-particle levels for reflection-asymmetric potentials (Leander *et al.*, 1985; Cwiok and Nazarewicz, 1989a, 1989b) were prepared to treat data in the vicinity of ^{145}Ba rather than nuclei in the vicinity of $A=151-155$. In consequence it is presently not feasible to assign appropriate asymmetrically deformed single-particle levels in the $A=151-155$ mass region where spectroscopic data are available. Thus we are not in a position at present to survey the rare-earth region in which octupole-quadrupole deformation is observed or expected, as we shall do in the actinides (Sec. VIII.A.1). We propose instead to discuss briefly, and in a general way to indicate, where the experimental and theoretical evidence suggests the region of octupole deformation might be in the rare earths. We shall give examples of octupole deformation in one odd-N nucleus (^{155}Gd) and one odd-Z nucleus (^{151}Pm), and we shall provide evidence of octupole deformation of a quite different nature, namely, the inverted odd-even staggering of differential radii.

1. The region of octupole deformation in the rare earths

The experimental evidence for octupole deformation in the Cs and Ba isotopes (Sheline, Jain, and Jain, 1988), together with the evidence from the level structures, suggests that the proton region, in which octupole deformation can be observed, extends from at least $_{55}$Cs to $_{64}$Gd. This is a larger proton region than in the actinides where it extends from $_{86}$Rn to $_{90}$Th or possibly to $_{92}$U (see Sec. VIII). This difference is not surprising, however. The $d_{5/2}$ and $g_{7/2}$ proton orbitals are nearly degenerate. This suggests that particle-hole 3^- configurations of the type $\pi d^{1}_{5/2}h^{-1}_{11/2}$ can occur over the approximate proton range of 56 to 64, as, in fact, experimentally observed. This may also imply that the octupole correlation effect for protons is somewhat lessened, since it is diluted by extending over a larger range. There is also experimental evidence that the neutron range of octupole deformation is Z dependent. At $Z=55$ or 56 the range of octupole correlation effects would appear to be from $N=84$ to 88 (or possibly 90; Sheline, Jain, and Jain, 1988); at $Z=63$ the range would be from 88 to 93 (Sheline and Sood, 1990a). In summary, the tentative suggestion of the region of octupole deformation on the chart of the nuclides would be an oval region beginning at Cs with $N=84$ to 88 and extending to Gd with a gradually increasing neutron range ending at $N=88$ to 93.

2. Examples of odd-N and odd-Z octupole deformed odd-A nuclei

The low-energy level scheme for ^{155}Gd is shown in Fig. 26 (Sheline and Sood, 1989). Bands of the same K, but with opposite parity, are seen to lie close together in energy and are labeled parity doublets (PD). There are six observed PD bands in ^{155}Gd with an average energy splitting of 122.0 keV. The nuclei ^{153}Sm and ^{151}Nd not shown here also exhibit a remarkably similar band structure. We have used the Nilsson quantum numbers to label the states, although parity mixing due to intrinsic reflection asymmetry tends to destroy the utility of these quantum numbers. However, the indicated Nilsson configuration is still the major component of the level. Another test of octupole deformation is to see if the E1 transition probabilities between PD's are faster than other E1's. Indeed, the slowest E1 transition involving PD's is 50 times faster than the fastest E1 transition, which does not involve parity doublets in ^{155}Gd and ^{153}Sm (Sheline and Sood, 1989).

We now look at the $K^\pi=1/2^\pm$ PD bands to see if the values of the decoupling parameters are approximately equal in absolute magnitude but of opposite sign. Among the four sets of $K^\pi=1/2^\pm$ PD bands only the $K^\pi=1/2^\pm$ bands at 367.6 and 422 keV in ^{155}Gd have enough band members known so that a decoupling parameter for each band can be determined. These values (0.23 and -0.47) are seen to be approaching a hybridized absolute value of ~0.35 and therefore lend further credence to the suggestions of octupole shape in ^{155}Gd.

The low-energy level scheme of ^{151}Pm is presented in Fig. 27 (Sood and Sheline, 1989a). The bands have been grouped together into four pairs of parity doublets. The $K^\pi=5/2^\pm$ PD, comprising mainly the [413] and [532] configurations, has been seen in practically every nuclide with energy splitting ranging from 1.2 keV in ^{157}Tb to about 200 keV in ^{153}Eu. The $K^\pi=3/2^\pm$ PD has a moderate splitting only in ^{151}Pm. In all other nuclei, the two bands are separated by ≥500 keV. The $K^\pi=7/2^\pm$ PD has been observed in ^{151}Pm, ^{155}Eu, and the lighter Tb and Ho isotopes. The $K^\pi=1/2^\pm$ PD, with [420] and [550] as the main configurations, is observed only in the

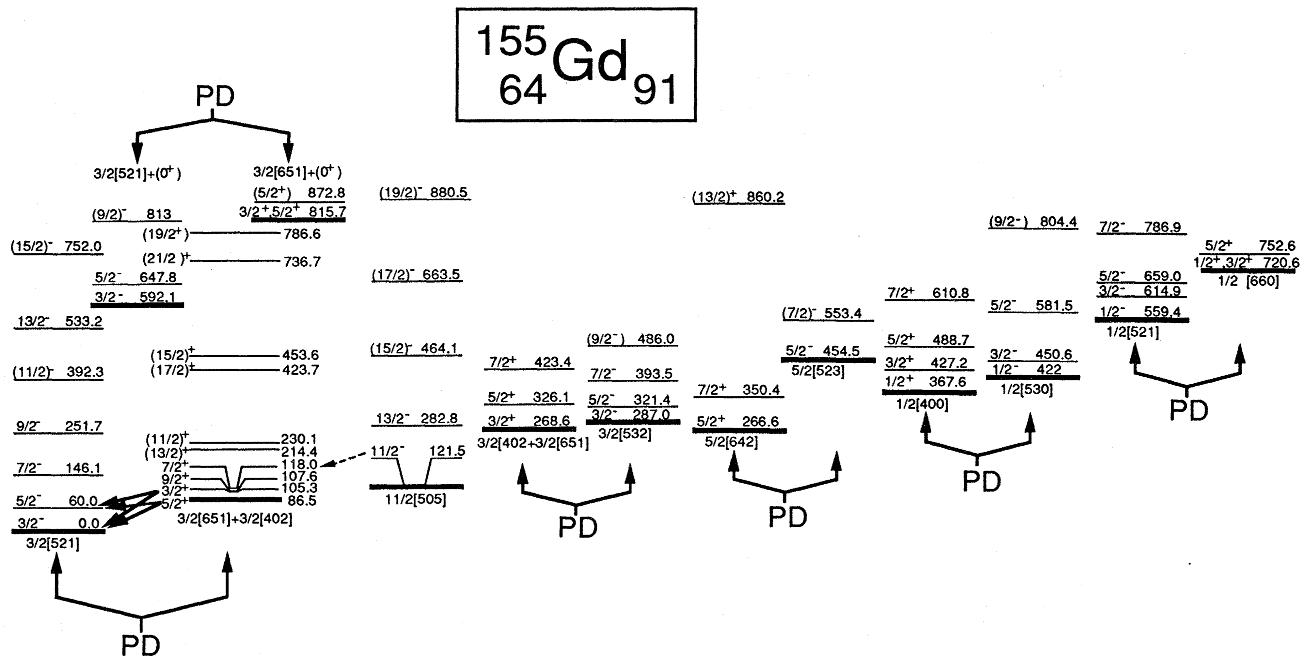

FIG. 26. Low-lying band structure of ^{155}Gd showing the proposed parity doublets (PD's) labeled by the major Nilsson configurations. E1 transitions for which transition probabilities have been determined are shown as bold arrows when between PD's and as dashed arrows when K forbiddenness is present. From Sheline and Sood (1989).

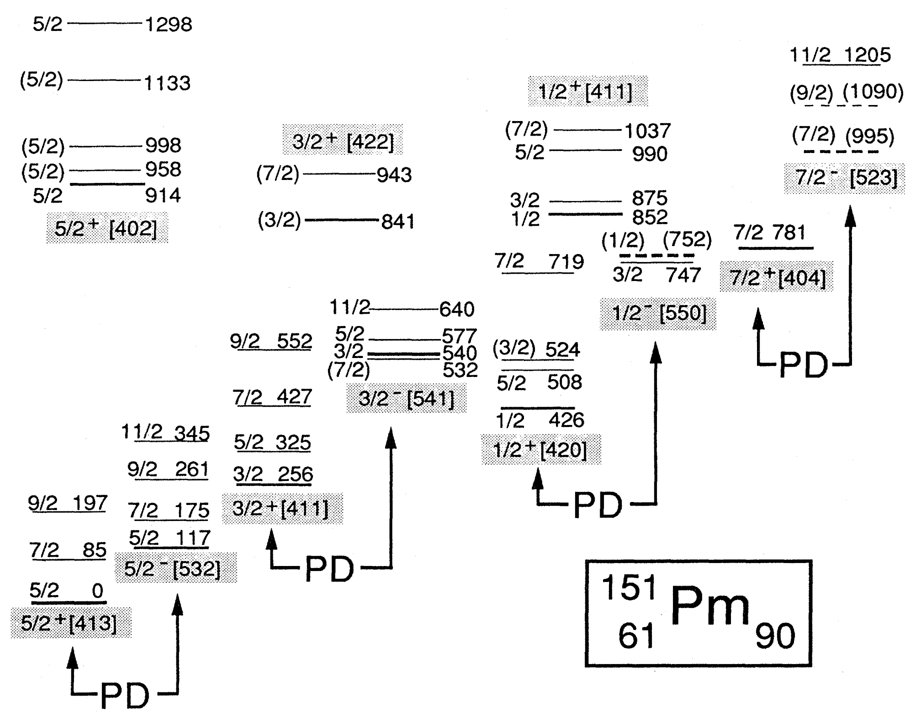

FIG. 27. Low-lying band structure of ^{151}Pm showing the proposed parity doublets (PD's) labeled by the major Nilsson configuration. From Sood and Sheline (1989).

^{151}Pm and ^{155}Eu nuclides. The $K^{\pi}=7/2^{\pm}$ and the $K^{\pi}=1/2^{\pm}$ PD's, expected in both ^{153}Pm and ^{153}Eu, have not been identified so far.

Several E1 transition rates of interest have been measured for levels in ^{151}Pm (Singh *et al.*, 1988). The E1 transitions connecting the parity doublet states are faster, by an order of magnitude or more, than the E1 transitions connecting non-PD states (Sood and Sheline, 1989a).

The magnetic moments of the $K^{\pm}$ parity doublet bandheads are predicted to be identical in the extreme limit of rigid octupole deformation with an infinite barrier between the mirror minima (Ragnarsson, 1983; Sheline and Leander, 1983). The calculated values, respectively, for the $5/2^{+}[413]$ and the $5/2^{-}[532]$ bandheads are given as 0.9 nm and 2.65 nm by Mottelson and Nilsson (1959) and as 1.42 nm and 2.65 nm by Ekström and Lamm (1973). The measured (Lederer and Shirley, 1978), value of 1.8(2) nm for the $5/2^{+}$ ground state of ^{151}Pm approaches the expected 2.0-nm hybridized value for the $K^{\pi}=5/2^{\pm}$ bands.

3. Inverted odd-even staggering of differential radii

The differential nuclear radii (differences in radii of nuclei and their isotopic neighbors with one less neutron $\delta\langle r^2\rangle^{N,N-1}$) are generally smaller for odd-A than for even-A nuclei. However, in the Rn (Borchers *et al.*, 1987), Fr (Coc *et al.*, 1987), and Ra (Ahmad *et al.*, 1988) nuclei with neutron number from 132 to 139 (except 134 for Fr), this odd-even effect is reversed and has been qualitatively related to octupole deformation. Similar evidence has been presented for Cs and Ba nuclei (Sheline, Jain, and Jain, 1988) and for Eu nuclei (Sheline and Sood, 1990a).

In Fig. 28 the differential nuclear radii for the Eu isotopes calculated from the experimental radii (Dorschel *et al.*, 1984; Ahmad *et al.*, 1985) are plotted against neutron number. The normal odd-even staggering is observed from neutron number 78 through 88 with the exception of the effect of shell closure at neutron number 82. However, from neutron number 88 through neutron number 93, the odd-even staggering is reversed. The onset of quadrupole deformation following neutron number 88 dramatically increases the differential nuclear radius at neutron number 89 (Brix, 1952). This in turn could make it difficult to separate the effect of quadrupole deformation from the effect of octupole deformation in the interpretation of the anomalous odd-even staggering at neutron number 89. In addition, the errors in the differential radii are quite large in the region from neutron number 88–93. However, the cumulative effects of the reversal of odd-even staggering all the way from neutron number 88 to 93 suggest the existence of octupole deformation in this region.

Please note that although all of these experimental facts are consistent with octupole deformation in some of

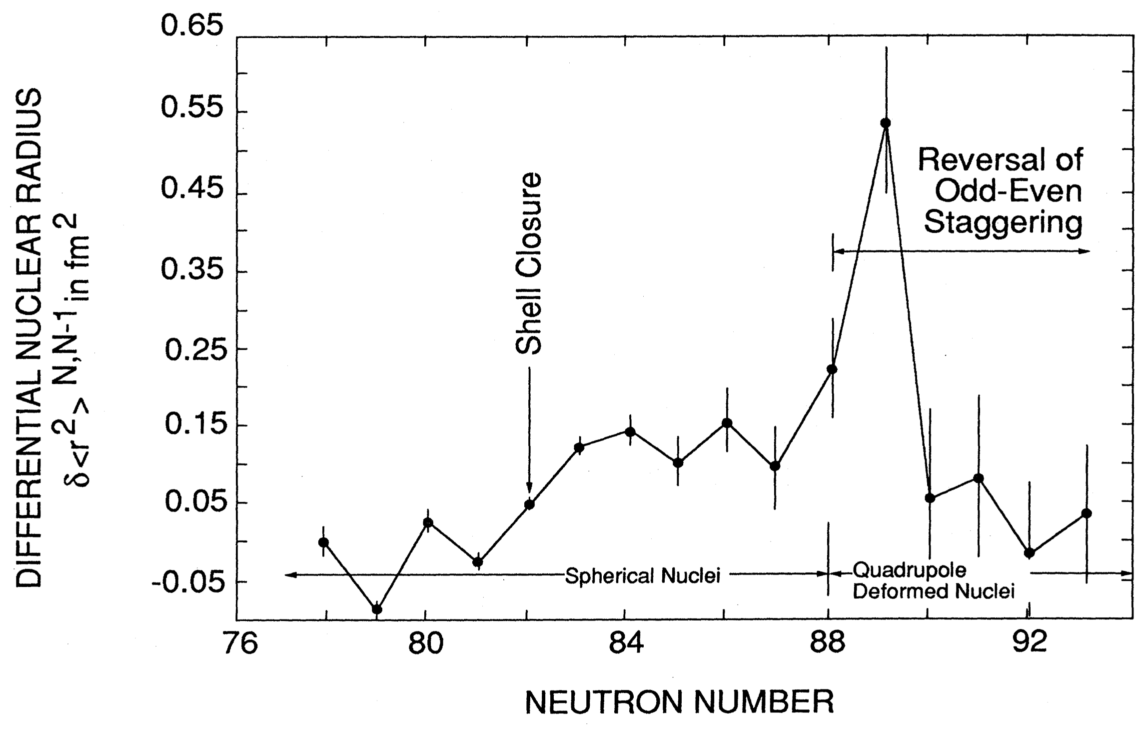

FIG. 28. Differential radii, $\delta\langle r^2\rangle^{N,N-1}$, the difference in radii of nuclei with N and $N-1$ neutrons as a function of neutron number N, for the Eu isotopes. The odd-even staggering is seen to reverse its phase from $N=88$ to 93, where octupole deformation is expected.

the rare-earth nuclei, they do not exclude the possibility of dynamic reflection asymmetry involving a very asymmetric harmonic-oscillator potential and multiphonon octupole excitation. Additional calculations, and particularly additional experiments, should be valuable in making this distinction.

D. Vibrational states

A strong E2 transition between the excited vibrational state and the one-quasiparticle base state clearly identifies its γ-vibrational character. On the other hand, a large internal-conversion coefficient implying a large E0 component is the signature of a β vibration, while somewhat enhanced E1 transitions to the base state imply octupole vibrations.

1. Mixed γ-vibrational states

The systematics of the vibrational excitations are presented in Figs. 29–31 (below). Figure 29 shows the vibrational energy difference for excitations that have a mixed one-quasiparticle-plus-gamma-vibrational character. Here, the vibrational energy is defined as the energy difference between the excitation energy of the mixed vibrational state and the base state forming the basis of γ vibration. For any given base state having projection quantum number K_0, two γ vibrations are obtainable from the couplings $|K_0-2|$ and (K_0+2). Most of the data known concern the $|K_0-2|$ excitation; furthermore, most of the data involve $K=1/2$ bands. We can see from Fig. 29 that the vibrational energy difference closely follows the systematics of γ-vibrational energy in even-even nuclei shown by the dashed line. Most of the data are concentrated in the mass range $A=164\pm10$, where the γ vibrations of even-even nuclei come down in energy, and vibrational admixture can be seen in states lying as low as 300–500 keV. On the other hand, nuclei in a comparatively narrow mass region around $A=175$ are seen to be very stiff towards γ vibration; consequently, no vibrational admixture is seen as high as 1 MeV or more. The situation changes around mass $A\geq185$, where the γ-vibrational excitation energy of the even-even system again decreases as the nuclei become particularly soft to γ deformation.

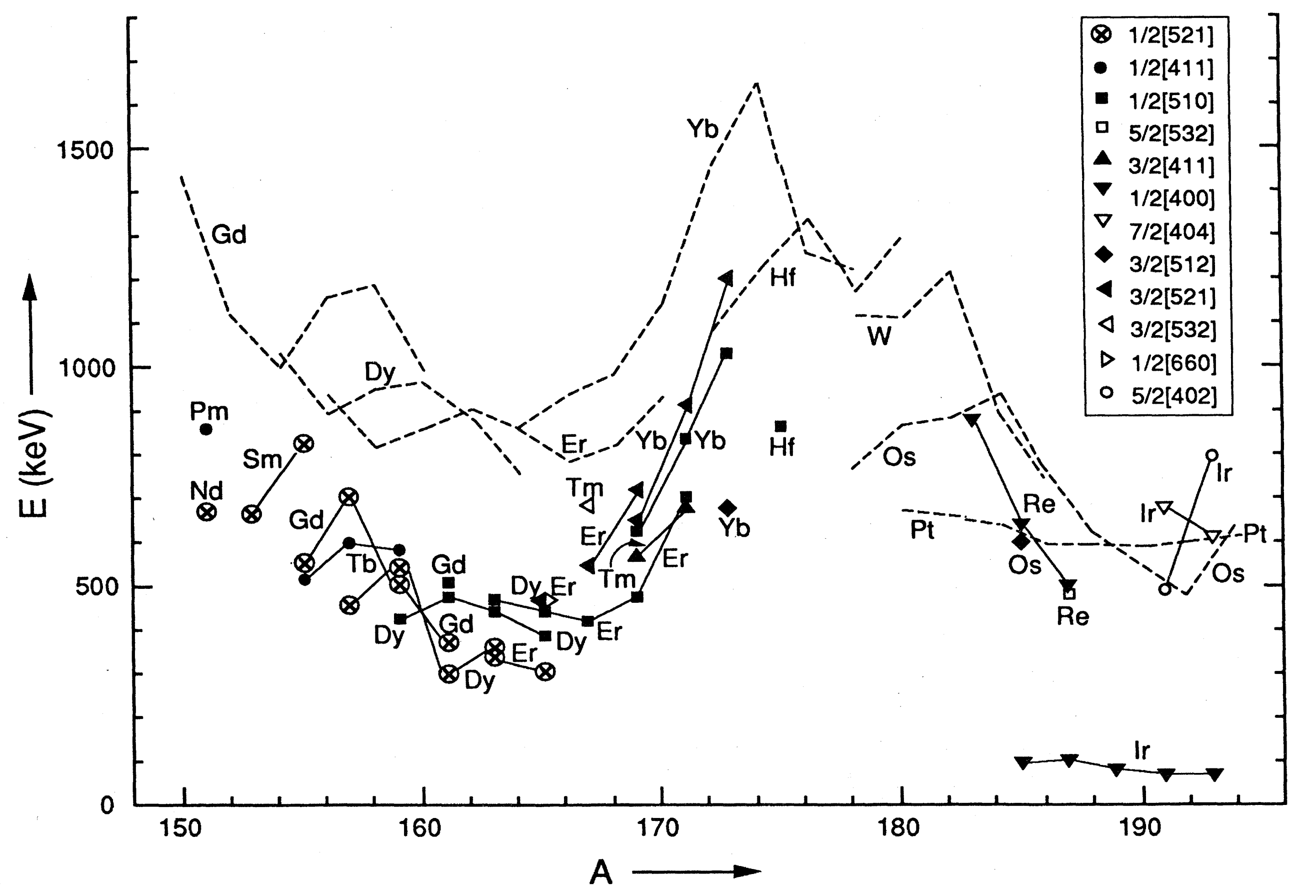

FIG. 29. Energy systematics of the one-quasiparticle states having mixed gamma-vibrational character in the rare earths. The vibrational energy, defined as the energy difference between the excitation energy of the mixed vibrational state and the base-state energy, is plotted. Also shown for comparison are the gamma-vibrational energies of even-even nuclei plotted as dashed lines.

More data are known for the case in which the γ vibration is mixed with the $1/2^-[521]$ one-quasineutron state than for any other. This state can mix with the $\{3/2^-[521]\otimes 2^+\}$ and the $\{5/2^-[523]\otimes 2^+\}$ vibrations. It is now understood that the $\{3/2^-[521]\otimes 2^+\}$ component contributes most for nuclei up to $A<160$. The $\{5/2^-[523]\otimes 2^+\}$ component then becomes more important; the systematics closely follows the systematics of the γ vibrations in even-even nuclei.

The next most observed one-quasineutron state having γ-vibrational admixture is the $1/2^-[510]$ state which mixes with the $\{5/2^-[512]\otimes 2^+\}$ vibration. Observed in Dy, Er, Yb, and Hf isotopes, the systematics of this state is also seen to follow the even-even systematics very closely.

It is interesting to note that few one-quasiproton states having vibrational admixtures are observed, although some have been seen in the Tb, Tm, and Re isotopes.

As expected, the admixed one-quasiparticle states in Ir lie very low in energy, indicating the large influence of γ deformation (axial asymmetry) in these nuclei. It is indeed remarkable that the $1/2^+[400]+\{3/2^+[402]\otimes 2^+\}$ state seen in the Ir isotopes has an almost flat energy variation that is quite similar to the behavior of γ excitation in the even-even Pt isotopes.

2. Relatively pure vibrational states

We show in Fig. 30 the vibrational excitation energy of relatively pure γ-vibrational states. It is clear from a comparison of Figs. 29 and 30 that the pure γ-vibrational states lie relatively closer to the vibrational excitations of even-even nuclei; some points actually lie on the dashed curves representing the even-even γ vibrations. The pure γ vibrations also follow the same general trend as that displayed by the even-even nuclei. Unfortunately, there are only two nuclei where the excitation energies of both members of the γ-vibrational multiplet are known; in both cases (^{165}Ho and ^{167}Er) the (K_0+2) member lies higher in energy than the $|K_0-2|$ member. This is to be expected because the zero-point rotational energy of the (K_0+2) band will always be larger than that of the $|K_0-2|$ band.

A similar vibrational energy systematics for the pure β-vibrational states is shown in Fig. 31. Again, for com-

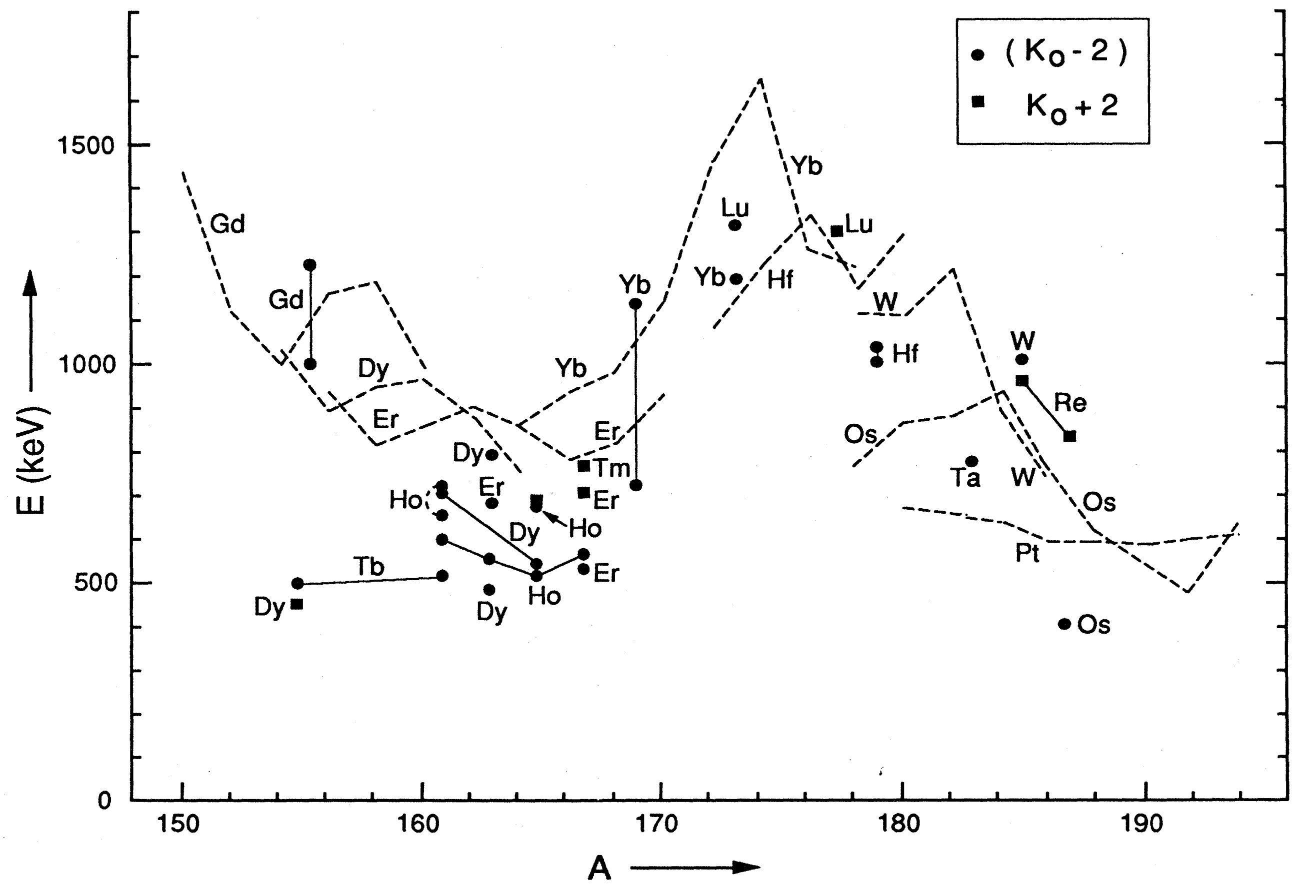

FIG. 30. Relatively pure gamma-vibrational energy systematics: ●, $|K_0-2|$ states; ■, (K_0+2) states. For comparison we include the gamma-vibrational energies of even-even nuclei shown by dashed lines.

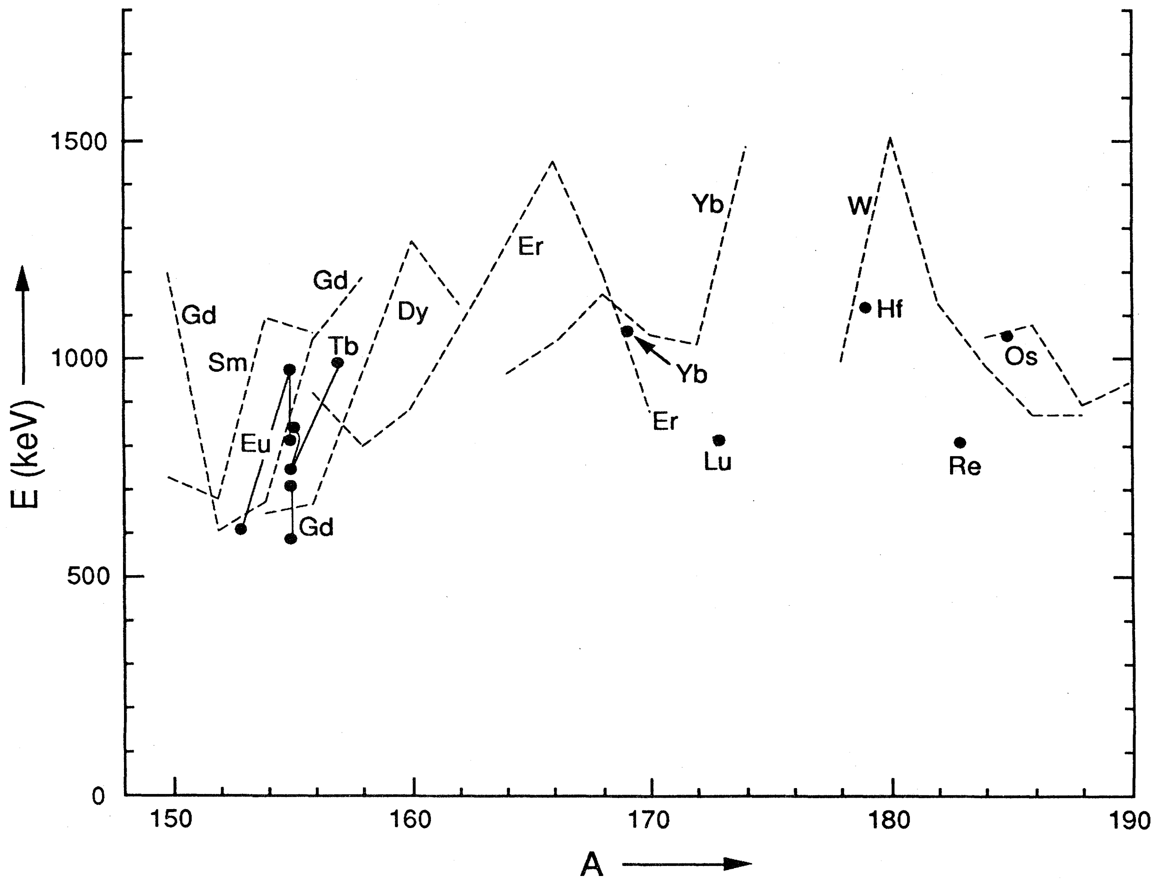

FIG. 31. Energy systematics of the beta-vibrational states in the rare earths. Dashed lines represent the beta-vibrational energies in even-even nuclei.

parison, we have also plotted the β-vibrational energy for even-even nuclei in this region. Most of the data points lie close to the even-even systematics and follow the same general trends.

Not much information is available on the moment-of-inertia parameter values and the decoupling parameter values (for $K=1/2$ bands) of vibrational bands. As is expected from theory, the moment-of-inertia parameters are, in general, smaller in magnitude than other bands in the same nucleus. The decoupling parameters for pure γ-vibrational bands are expected to be zero. However, they are found to have finite values in those cases for which data are available, implying some one-quasiparticle admixture.

VII. EMPIRICAL DATA ON INTRINSIC STATES IN THE ACTINIDE REGION ($A \geq 221$)

A. Data on octupole-quadrupole deformed nuclei ($221 \leq A \leq 229$)

The empirical data on intrinsic excitations for the nuclei in the mass range $221 \leq A \leq 229$ are summarized in Tables XXIX and XXX. The format of the tables is similar to that of the data tables for rare earths, with the difference that the intrinsic states have been assigned configuration in terms of the expectation values of the spin and parity operators $\langle \hat{s}_z \rangle$ and $\langle \hat{\pi} \rangle$ and if $K=1/2$, also a_p defined in Sec. III. Not enough data are available for ^{221}Th, ^{225}Th, ^{227}Th, and ^{227}Pa, and they are not included in these tables. However, they have been taken into account in the discussion in Sec. VIII.

B. Data for nuclei $A \geq 231$

The empirical data on intrinsic states for the $A \geq 231$ region are summarized in Tables XXXI to XXXV for odd-Z, and Tables XXXVI to XLII for odd-N nuclei. These tables have the same format as the tables for rare earths, and the same explanations apply. Since α decay becomes possible in the actinides, a favored α transition is shown in the tables by adding a subscript α to the excitation energy value.

TABLE XXIX. Intrinsic states of odd-A, odd-Z octupole deformed nuclei with $A=221$ to 229; the quantum numbers used for labeling the configurations in the first column are described in footnote g and in Sec. III.A.3 in the text.

	^{221}Fr^{a,l}	^{225}Fr^{b}	^{223}Ac^{c}	^{225}Ac^{d}	^{227}Ac^{e,n}	^{229}Pa^{f}
$1/2^-$ $(-0.1,-0.5,$ $-2.0)^g$	(5) 0^h 5.2 4.3					
$1/2^+$ $(-0.1,-0.5,$ $-2.0)$	(3) 99.8 5.8 −3.64 7.2					
$3/2^-$ (0.1,0.0)	36.6^i	$0^{j,k}$ 5.7				
$3/2^+$ (0.1,0.0)	224.6^i ~ 7.5	142.6				
$3/2^-$ $(0.0,-0.3)$	552.6		4.1 9.3	0^m 6.0 7.4	0 6.0	
$3/2^+$ $(0.0,-0.3)$			88.9 4.3	40.1^m 4.9 6.9	27.4 3.8 6.7	
$5/2^-(0.0,-0.2)$ ↓ (0.2,0.4)			0_α 6.0	120.8^m 7.1 >10	273.1 6.3	~ 0.2
$5/2^+(0.0,-0.2)$ ↓ (0.2,0.4)			65 6.43	155.6^m_α 6.3 >10	304.7 5.3 6.7	0
$1/2^-$ $(0.2,-0.1,$ 2.0)					(3) 330.0^o 6.7 −2.21 6.7	
$1/2^+$ $(0.2,-0.1,$ 2.0)					(5) 425.7^p 5.8 4.83 7.0	
$1/2^-[530]$						(3) 122.7 6.9 −1.58
Other levels	q					r

^{a}Toth and Ellis (1979): NDS; Table of Isotopes (Lederer and Shirley, 1978), Coc *et al.* (1985): I; Dzhelepov *et al.* (1972): α decay; Vylov *et al.* (1977): β decay.

^{b}Coc *et al.* (1985): I; Burke *et al.* (1988): β decay and (t,α).

^{c}Table of Isotopes (Lederer and Shirley, 1978), Sheline, Liang, and Paris (1990): α decay.

^{d}Aguer *et al.* (1973): α decay; Ahmad *et al.* (1984): α decay and β decay.

^{e}Maples (1977b): NDS; Teoh *et al.* (1979), Anicin *et al.* (1982): α decay; Lourens *et al.* (1971), Börner *et al.* (1979): β decay; Martz *et al.* (1988): $(^3\mathrm{He},d)$, (α,t).

^{f}Ahmad *et al.* (1982): EC,(p,t).

^{g}All of these bands (except one) are assigned as octupole parity doublets (PD) and are labeled by the values $\langle \hat{s}_z \rangle$, $\langle \hat{\pi} \rangle$, and $\langle \pi\ \mathrm{conj} | -\hat{j}_+ | R\ \mathrm{conj} \rangle$. See the text for details of the octupole single-particle-state labeling.

^{h}The decoupled nature of the $I=5/2$ ground state is confirmed by a negative quadrupole moment of -1.0 barn; its magnetic moment of $1.58\mu_N$ agrees with observed values of decoupled $h_{9/2}$ $5/2^-$ proton states in other nuclei, which range from $1.4\mu_N$ to $2.6\mu_N$. Low-lying positive-parity states are found to be connected to the ground band by the E1 transition, as is expected when octupole deformation is present.

^{i}Highly perturbed bands possibly due to mixing with $K=\frac{1}{2}$ bands.

^{j}The $3/2^-[532]$ assignment seems to be most appropriate from an analysis of the (t,α) cross-section data (Burke *et al.*, 1988). However, the presence of an octupole shape does not affect these values in a crucial way, and the question of the presence of the octupole shape in this nucleus remains open. Coc *et al.* (1985) have observed a reversal in the odd-even staggering of the isotope shift at ^{227}Fr, implying the cessation of octupole deformation at $N=140$. Some octupole effect in ^{225}Fr is therefore probable.

TABLE XXIX. (*Continued*).

[k]The ground state of ^{223}Fr is also measured to be $I^{\pi}=3/2^-$ and may be assigned a similar character. Some excited states in ^{223}Fr are also known (Lederer and Shirley, 1978). In particular, a 518-keV level was assigned as $3/2^-[532]$, which may actually be the $3/2^-$ $(0.0,-0.3)$ octupole state.

[l]Low hindrance factors in both the ground and excited region of the level scheme of ^{221}Fr probably correspond to a situation of very small deformation and a large mixing of states, which are ~ 500 keV apart. It implies that ^{221}Fr is a hybrid nucleus where the deformed Nilsson orbitals are beginning to collapse into more degenerate shell-model states.

[m]Large enhancements in the E1 transition rates have been observed by Ahmad *et al.* (1984) for the interband transitions of the $K=3/2^{\pm}$ and $K=5/2^{\pm}$ parity doublet bands.

[n]This nucleus lies at the border of the octupole-quadrupole and the quadrupole deformation regions. Sheline and Leander (1983) interpret this nucleus as having a core with "soft" octupole deformation. All the states given here are interpreted as parity doublets. The hybrid values of the intrinsic gyromagnetic ratio and the values of the decoupling parameters support this interpretation. The usual Nilsson assignments starting from the top of the table are $3/2^-[532]$, $3/2^+[651]$, $5/2^-[523]$, $5/2^+[642]$, $1/2^-[530]$, and $1/2^+[660]$. The spectroscopic strengths of one-proton stripping reactions as measured by Martz *et al.* (1988), however, seem to be in better agreement with those calculated for the reflection-symmetric potential.

[o]The $1/2^-$ state lies at energy 354.6 keV.

[p]The $1/2^+$ state of this band lies at 435.4 keV.

[q]A highly tentative set of $K=3/2^{\pm}$ and $K=5/2^{\pm}$ parity doublets is proposed by Liang, Péghaire, and Sheline (1990) among a group of states with the energies $(5/2^+)$ 517.6 keV, $(3/2^-)$ 551.9 keV, $(7/2, 5/2^+)$ 570 keV, and (5/2) 630.3 keV. However, only the $3/2^-$ state at 551.9 keV can be considered firm. These bands, lying so close to each other, will be highly mixed.

[r]The 1/2, 5/2, and 7/2 members of the $1/2^-[530]$ band are observed at 140±2, 217±3, and 187±3 keV, respectively. Also observed are positive-parity levels at 211 and 242 keV with possible spin assignments of 1/2 and 3/2, respectively. The two $K=1/2^{\pm}$ states can also be interpreted as octupole parity doublets with the assignment $(0,2-0.1,2)$.

TABLE XXX. Intrinsic states of odd-A, odd-N octupole deformed nuclei with $A=221$ to 229. The quantum numbers used for labeling the configurations in the first column are described in footnote i and in Sec. III.A.3 in the text.

	^{221}Ra[a]	^{223}Th[b]	^{223}Ra[c]	^{225}Ra[d]	^{227}Ra[e,g]	^{229}Th[f,h]
$5/2^+$ (0.2,0.2)[i]	0 7.6	0 7.3	234.9 6.5 6.1			
$5/2^-$ (0.2,0.2)	103.4 6.2	(9) 180 5.7	369.4 5.1 6.6			
$3/2^+$ $(-0.1,0.6)$	321.4 7.5		0[j] 6.0			
$3/2^-$ $(-0.1,0.6)$	450.2[k] 7.0		50.2 5.9 5.7			
$1/2^+$ $(0.2,-0.1,$ 3)			286.2 8.6 1.18 8.2	0[l] 5.6[m] 1.5		
$1/2^-$ $(0.2,-0.1,$ 3)			(3) 329.5[n] 6.8 -2.0 $\sim$7.9	(3) 31.6 4.9 -2.6		
$3/2^+$ (0.3,0.3)				149.9 6.0 6.6	0 5.2	$\sim$0.1 5.8
$3/2^-$ (0.3,0.3)[o]				225.1 7.0 6.2	90.0 2.4	164.5 10.5
$5/2^+[633]$				236.7[p] 4.5 6.7	1.7 5.1[q]	0_{α} 6.1 5.6[r]

TABLE XXX. (*Continued*).

	^{221}Ra[a]	^{223}Th[b]	^{223}Ra[c]	^{225}Ra[d]	^{227}Ra[e,g]	^{229}Th[f,h]
$5/2^-$ $(-0.2,0.7)$[o]						146.4 3.1 7.2
$1/2^+$ $(-0.1,0.6,$ $1)$					120.7 8.3 0.62	261.9 6.9 0.30
$1/2^-$ $(-0.1,0.6,$ $1)$					(3) 284.3[s] (6.0) (−1.68)	535.5
$1/2^-[770]$					(3) (471.6) 6.5	
$1/2^-[501]$					(675.9) 9.9[t] 0.87 5.5	
$1/2^-[761]$					(3) (756) (6.0) (1.83)	
$5/2^-$ $\{5/2^+[633]\otimes 0^-\}$ $\{5/2^+[622]\otimes 0^-\}$					475.0	512 7.1
Other levels				u		

[a]Ahmad, S. A., *et al.* (1983): *I*; Liang *et al.* (1988), Ackerman *et al.* (1989): α decay.
[b]Dahlinger *et al.* (1988): $(^{18}O,3n)$.
[c]Maples (1977a): NDS; Ahmad, S. A., *et al.* (1983): *I*.
[d]Toth (1979): NDS; Ahmad, S. A., *et al.* 1983: *I*; Ishii *et al.* (1985), Helmer *et al.* (1987): α decay; Sheline *et al.* (1983), Nybø *et al.* (1983): (d,t), $(\mathbf{d},t)$, and β decay; Andersen *et al.* (1989): β decay; Løvhøiden *et al.* (1986): $(^3He,\alpha)$.
[e]von Egidy *et al.* (1981): β decay, (n,γ), (d,p), $(\mathbf{t},d)$.
[f]Toth (1978): NDS; Gerstenkorn *et al.* (1974): I,μ; Ahmad *et al.* (1982): EC; Kroger and Reich (1976): α decay; Braid *et al.* (1976): (d,t).
[g]The lowest $K=1/2^{\pm}$ and $K=3/2^{\pm}$ bands have been interpreted as octupole deformed PD bands. However, no PD could be observed for the 1.74-keV, $K=5/2^+$ band, and it is assigned to the usual Nilsson configuration $5/2^+[633]$ indicating the coexistence of reflection-symmetric and reflection-asymmetric shapes (Sheline, 1989). The polarization effect of the odd particle has an important role to play in the coexistence phenomenon (Sheline, Jain, *et al.*, 1989).
[h]A detailed analysis of this nucleus has been presented by Leander and Sheline (1984) and Leander and Chen (1988). According to the intermediate coupling scheme used by Leander and Sheline, this nucleon displays shape coexistence, and the ground state is a reflection-symmetric Nilsson level; the $5/2^-$ state at 512 keV is the "anharmonic" octupole "phonon" excitation built on the ground state. The $K=3/2^{\pm}$ states show parity mixing and may be interpreted as PD bandheads with $\epsilon_3 \sim 0.07$. The fixed deformation model used by Leander and Chen (1988) gives a similar interpretation. It cannot entirely explain the energy splitting of $K=5/2$ PD, as expected. Furthermore, the $K^\pi=1/2^+$ band has a decoupling factor of positive sign due to the octupole deformation; a negative sign is obtained for the $1/2^+[631]$ orbit that would be assigned to these bands in a reflection-symmetric scheme. A second $K^\pi=5/2^+$ band whose 9/2 level tentatively lies at 426 keV is interpreted by Leander and Chen as the parity doublet of the second $K^\pi=5/2^-$ band at 146 keV.
[i]Most of these bands are interpreted as octupole deformed parity doublet (PD) bands and are labeled by the values $\langle \hat{s}_z \rangle$, $\langle \hat{\pi} \rangle$, and $\langle \pi \text{ conj} | -\hat{j}_+ | R \text{ conj} \rangle$. See the text for details of the octupole single-particle-state labeling. In most of the nuclei, the members of the opposite parity bands forming PD are observed to be connected by relatively strong E1 transitions.
[j]Sheline (1986) and Sheline, Chen, and Leander (1988) have reassigned the ground-state spin to be 3/2 and parity positive from a fresh analysis of the angular correlation and other data. This in turn also requires that the ground-state spin of ^{227}Th be assigned as $1/2^+$, as compared to the earlier assignment of $3/2^+$.
[k]The assignment of $I^\pi=3/2^-$ to 450.2 keV is not consistent with the γ decays of the $3/2^-$ and the $5/2^-$ (485.4) levels.
[l]The positive value of the decoupling parameter $a=1.5$ for the $K=1/2^+$ band cannot be explained in the Nilsson model, where it is predicted to be negative. The existence of octupole deformation explains this sign change. Leander and Chen (1988) also point out that the α transitions to the negative-parity members of the $K=1/2$ band are suppressed; this can be very well accounted for by the octupole deformed rotor-plus-particle coupling, which gives a nonadiabatic mixture of the α-favored $K=5/2$ component into the $K=1/2$ bands that is larger for positive than for negative parity.
[m]Values calculated from 1/2, 3/2, and 9/2 level energies.

TABLE XXX. (*Continued*).

[n]The 1/2 level lies at 350.0 keV.
[o]Strong Coriolis mixing between these two bands is expected.
[p]An $I^\pi = 15/2^-$ level was thought to be the only known member of the $K = 5/2^-$ band, thus forming a $K = 5/2^\pm$ PD with the 236.7-keV band (Leander and Chen, 1988). However, an analysis of the data and calculations including the polarization effects of the odd particle suggest that the 538-keV state is a member of the $K = 3/2^-$ band beginning at 225.1 keV (Sheline, Jain, *et al.*, 1989). The $K = 5/2^+$ state is interpreted as the reflection-symmetric $5/2^+[633]$ orbital, thus indicating shape coexistence in this nucleus.
[q]Calculated from the 5/2 and 9/2 level energies.
[r]The $\log ft$ value is a combined value to both the 5/2, $5/2^+[633]$ and the $3/2^+$ states.
[s]The 1/2 level lies at 296.58 keV.
[t]The large value of $\hbar^2/2\mathfrak{J}$ may be compared with a value of 10.4 keV with a probable assignment of $1/2^-[501]$ in ^{225}Ra. See footnote u.
[u]Other strongly populated levels in (d,t) and $(^3\text{He},\alpha)$ reactions are 898 keV $(1/2^-)$, 1225 keV $(5/2^-)$, and 1258 keV $(3/2^-)$. Two levels at 956 keV $(5/2^-)$ and 967 keV $(3/2^-)$ are probably members of the 898-keV band, giving, however, a very large value of $\hbar^2/2\mathfrak{J} = 10.4$ keV and a decoupling parameter $a = 1.21$; an assignment $1/2^-[501]$ is proposed. Three more levels lying at 1258, 1408, and 1441 keV are strongly populated in the (d,t) reaction and all are assigned $I^\pi = 3/2^-$. Nybø *et al.* (1983) consider these three levels to be the major fragments of the 1258-keV level assigned the Nilsson configuration of $3/2^-[501]$. Many other unassigned levels, mostly with positive parity, have also been seen. An important result from the work of Andersen *et al.* (1989) is the observation of the 394-keV level, which has negative parity and spin $(3/2^-, 5/2^-)$. It is possible that this level $(I^\pi = 5/2^-)$ forms a parity doublet with the 236.7-keV level. Among other measurements on this nucleus, Reich *et al.* (1986) report an enhanced $\Delta K = 0$, E1 transition probability between PD $K = 1/2^\pm$ bands. However, the deduced $\Delta K = 1$, E1 strength, though small, was found to be large for a reflection-asymmetric shape.

TABLE XXXI. Intrinsic states of $Z = 89$ and $Z = 91$ odd-A nuclei.

$_{89}$Ac	$A = 229$[a,g]	231[b]	$_{91}$Pa 231[c]	233[d]	235[e]	237[f]
$1/2^-[530]$	(3) 102 (6.0) (−0.75)	(3) ~38 (6.0) (−1.33)	(3) 0[h] 6.2 −1.49 9.5	(3) 0[i] 5.9 −1.37 5.9	(3) 0[j] ~3.6 ~−0.35 ~6.0	(3) 90[k] (6.0) (−1.25)
$5/2^-[523]$			(174.1) 6.3 6.9	(257.3) 6.2		
$5/2^+[642]$			183.5_α 9.1 5.94	237.9_α 9.7		
$3/2^-[521]$			(604) 5.6	(679.9) 6.8		
$3/2^+[651]$[l]	0 1.0	(9) (76) 2.5	(5) 84.2[m] 2.5 5.9	(5) 86.5[n] 2.5 6.5	(9) 65[o] 2.8 ~6.0	(9) 105 2.2
$1/2^+[400]+$ $1/2^+[660]$	151 (6.0) (1.22)	0 (6.0) (1.11)	(287) (6.0) (0.72)	169.1 6.5 0.67 ~7	19 (6.0) (0.89) ~6.0	0 (6.0) (0.94)
$3/2^-[532]$	(5) 70 7.1		320.2 6.3 6.75			
$3/2^+[402]$	336 6.0	(235) 4.4		444	(345) 6.6	364 5.8
$9/2^-[514]$		(11) 671		(11) (980)	(11) (751)	(11) (624)
$1/2^-[541]$		(5) (797)		(5) (1065)	(5) (965)	(5) (1025)
Other levels	p			q		

TABLE XXXI. (*Continued*).

[a]Toth (1978): NDS; Thompson *et al.* (1977): (t,α).
[b]Schmorak (1983): NDS; Thompson *et al.* (1977): (t,α).
[c]Schmorak (1983): NDS; Hornshøj *et al.* (1975), Börner *et al.* (1979): β decay; Browne and Asaro (1973): α decay and β decay; Erskine *et al.* (1975): (α,t).
[d]Marrus *et al.* (1961): I. Hoekstra and Wapstra (1969): β decay; Elze and Huizenga (1975): $(^3He,d)$, (α,t); Gonzalez *et al.* (1979): α decay; Thompson *et al.* (1977): (t,α).
[e]Schmorak (1983): NDS; Mirzadeh *et al.* (1986): β decay; Thompson *et al.* (1977): (t,α).
[f]Ellis-Akovali (1986): NDS; Thompson *et al.* (1977): (t,α).
[g]This nucleus lies at the border of the limited octupole-quadrupole deformation region. Leander and Chen (1988) interpret the bands by assuming a very small value of octupole deformation. A fair agreement was obtained by Thompson *et al.* (1977) in Coriolis-coupling calculations without octupole. However, inclusion of octupole seems to improve the agreement. The lowest four states are thus interpreted as $K=3/2^{\pm}$ and $1/2^{\pm}$ PD states. In addition, three levels observed at 422 keV $(7/2^-)$, 464 keV $(9/2^-)$, and 489 keV $(11/2^-)$ are tentatively assumed to belong to a second $K=3/2^-$ band, the PD band of $K=3/2^+$ at 336 keV.
[h]The 1/2 level lies at 9.22 keV.
[i]The 1/2 level lies at 6.67 keV.
[j]The 1/2 level lies at ≈ 7 keV.
[k]The 1/2 level of this band is not known.
[l]Strong Coriolis mixing present. Some $\Delta N=2$ mixing is also expected. The moment-of-inertia parameter is calculated from the 9/2 and 13/2 states or from the 5/2 and 9/2 states if 5/2 lies lowest.
[m]The 3/2 level lies at 102.3 keV.
[n]The 3/2 level lies at 94.7 keV.
[o]The 3/2 level has been tentatively located at ≈ 50 keV.
[p]Tentative assignments of (11/2, 9/2$^-$[514]) and (5/2, 1/2$^-$[541]) have been made to levels at 930 and 1004 keV (Thompson *et al.*, 1977).
[q]On the basis of Coriolis-mixed calculations of differential cross section, Elze and Huizenga (1975) suggest the 529-keV and 589-keV levels to be the 13/2, 1/2$^+$[660] and 13/2, 5/2$^+$[642] states. In addition, from the β decay of ^{233}Th produced in the $^{232}Th(n,\gamma)$ reaction, Börner *et al.* (1979) have obtained high-precision data on low-lying-level energies. The following levels have no match with the already known and assigned levels: 447.7, 454.4, 553.9, 585.5, and 764.6 keV.

TABLE XXXII. Intrinsic states of $Z=93$ odd-A nuclei.

$_{93}$Np	$A=233$[a]	235[b]	237[c]	239[d]	241[e]
5/2$^+$[642]	0	0	0 4.7 6.83	0 4.4 6.6	0
5/2$^-$[523]	50_α	49.1_α 6.1	59.5_α 6.2 8.5 7.32	74.7_α 6.2 5.92	
3/2$^-$[521]		(565) 7.4	(514.2) 6.3	(448.2) 6.8	
7/2$^-$[514]		(922) 6.2		(992.2) 6.3	
7/2$^+$[633]		(13) (1160)		(9) 864.9 6.5[f]	
5/2$^-$[512]		(7) (1845)			
1/2$^-$[530]		(3) 352[g] 5.7 −2.10	(3) 267.5[h] 6.9 −1.67 6.6	(3) 260.8[i] 4.7 −1.71	
3/2$^+$[651]				(9) 346.8	

TABLE XXXII. (*Continued*).

$_{93}$Np	$A=233$[a]	235[b]	237[c]	239[d]	241[e]
$1/2^+[400]$			332.4	(220.2)	
+			6.2 1.08	7.2 0.76	
$1/2^+[660]$			7.3		
		834			
$5/2^+$					
$\{5/2^+[642]\otimes 0^+\}$					
$5/2^-$			721.9	662.3	
$\{5/2^+[642]\otimes 0^-\}$			4.9	4.7	
$+\{5/2^-[523]\otimes 0^+\}$				7.4	

[a]Ellis (1978): NDS.
[b]Schmorak (1983): NDS; Friedman *et al.* (1974): (p,t); Gorman and Asaro (1971): α decay and EC; Jäger *et al.* (1973): EC; Griffioen *et al.* (1978): (^{3}He,d), (α,t).
[c]Ellis-Akovali (1986): NDS; Elze and Huizenga (1970a): (^{3}He,d), (α,t); Thompson *et al.* (1976): (d,d'); Ellis *et al.* (1979), I. Ahmad, *et al.* (1983): EC; Simon *et al.* (1980), Kulessa *et al.* (1983): Coul.; Yamazaki and Hollander (1966): β decay; Lederer *et al.* (1966), Baranov *et al.* (1964): α decay.
[d]Schmorak (1983): NDS; Blinowska *et al.* (1964), Börner *et al.* (1979): β decay; Baranov *et al.* (1964), Lederer *et al.* (1966), Engelkeimer (1969), Van Hise and Engelkeimer (1968): α decay; von Egidy *et al.* (1975): (^{3}He,d), (α,t).
[e]Ellis-Akovali (1985): NDS.
[f]Value calculated from the 9/2 and 13/2 levels.
[g]The 1/2 level possibly lies at 371 keV.
[h]The 1/2 level lies at 281.35 keV.
[i]The 1/2 level lies at 270.9 keV.

TABLE XXXIII. Intrinsic states of $Z=95$ odd-A nuclei.

$_{95}$Am	$A=239$[a]	241[b]	243[c,i]	245[d]
	0	0	0	27.9
$5/2^-[523]$	5.8	5.9	6.0	6.1
			6.4	
	558_{α}	471.8_{α}	266.0_{α}	154
$3/2^-[521]$	5.8	6.5	6.8	
		7.68		
		(11) (732)	465.7	327.2_{α}
$7/2^+[633]$[e]			7.4	7.6
			5.5	7.3
		(9) (1163)	(9) (977)	
$7/2^-[514]$				
	187	205.9	84.0[f]	0
$5/2^+[642]$[e]	4.7	4.2	3.6	
			≥ 6.3	
$1/2^+[400]$		623.1		
+		(6.0) (0.67)		
$1/2^+[660]$		8.04		
		(3) 636.9[g]		
$1/2^-[530]$		(6.0) (-1.85)		
		6.24		
		670.2[h]		
$3/2^+[651]$				
		7.7		
$5/2^-$		(952)		
$\{5/2^-[523]\otimes 0^+\}$				
Other levels		j		k

TABLE XXXIII. (*Continued*).

[a]Porter *et al.* (1972): ^{239}Am EC decay; I. Ahmad (1966): α decay.
[b]Ellis-Akovali (1985): NDS; Porter *et al.* (1974): α decay and EC; Friedman *et al.* (1974): (p,t); Erskine *et al.* (1975): (α,t).
[c]Ellis-Akovali (1981a): NDS; Bemis *et al.* (1981): Coul.; Friedman *et al.* (1969): α decay and β decay; Hoffman *et al.* (1969): β decay; Elze and Huizenga (1970b): (^{3}He,d), (α,t).
[d]Ellis-Akovali (1981a): NDS; Daniels *et al.* (1968): β decay; Chasman *et al.* (1977), Börner *et al.* (1979): α decay.
[e]Strong Coriolis mixing is present.
[f]The 5/2 and 7/2 members of the $5/2^+[642]$ band were not observed in (^{3}He,d) and (α,t) reactions.
[g]The 1/2 level of this band lies at 652.09 keV.
[h]Calculations of Gareev *et al.* (1971) suggest an admixture of β vibration in this state.
[i]Theoretical calculations with quasiparticle-phonon mixing in this nucleus are presented by Komov *et al.* (1972).
[j]Erskine *et al.* (1975) report many unassigned levels between 880 and 1230 keV.
[k]Two levels at 887.47 keV ($7/2^+$) and 957.53 keV ($9/2^+$) may belong to a $K=7/2$ band, which remains unassigned. According to the calculations of Komov *et al.* (1972), it may be the $\{5/2^-[523]\otimes 1^-\}$ octupole vibrational band.

TABLE XXXIV. Intrinsic states of $Z=97$ odd-A nuclei.

$_{97}$Bk	$A=243$[a]	245[b]	247[c]	249[d]	251[e]
$3/2^-[521]$	(0)	(0_α)	0_α	8.8_{iso} 6.2 5.9	0 6.5 6.15
$7/2^+[633]$			40.8[f] 4.7	0_α 4.6	$35.7_{\alpha,iso}$ 4.5
$1/2^-[521]$			704 6.3[g] 0.89[g]	(643.2)[h] (6.0) (0.02) 5.9	542.6 (6.0) (0.11) 6.13
$7/2^-[514]$			(9) (904)	(9) 750.7[i] 7.2	
$9/2^+[624]$			(13) (1166)[j]	(13) (1229)	
$5/2^+[642]$			334.9[f] 6.2	389.2 5.7	269.3 7.38
$5/2^-[523]$			447.8 5.9 6.4	(9) (621.9)	
$1/2^+[400]$			(487) (6.0) (0.72)	377.6 6.6 0.69	311.7 7.89
$1/2^-[530]$				(3) 558.2[h] 4.8 −1.76 ~7	(3) 422.3[k] (6.0) (−1.88) 7.14
Other levels				1	

[a]Ellis-Akovali (1981a): NDS.
[b]Ellis-Akovali (1981a): NDS.
[c]Ellis-Akovali (1981b): NDS; I. Ahmad *et al.* (1979): (α,t) α decay, and β decay.
[d]Schmorak (1981a): NDS; Holtz and Hollander (1970), Ahmad and Milsted (1975): α decay; Erskine *et al.* (1975): (^{3}He,d), (α,t); Hoff, Evans, *et al.* (1971), Hoff (1975): β decay; Bemis *et al.* (1982): Coul.

TABLE XXXIV. (*Continued*).

[e]Schmorak (1981b): NDS; Lougheed *et al.* (1978): β decay; Fields *et al.* (1967): α decay.
[f]Bandheads of $7/2^+[633]$ and $5/2^+[642]$ bands were not seen in the (α,t) reaction.
[g]Values calculated from the 1/2, 5/2, and 7/2 level energies.
[h]The 1/2 level of the $1/2^-[530]$ band lies at 569.2 keV. Calculations of Gareev *et al.* (1971) suggest a complex structure of these two states. Thus the $1/2^-[530]$ state has an admixture of $\{3/2^-[521]\otimes 2^+\}$ and $\{1/2^-[521]\}$, while the state $1/2^-[521]$ has an admixture of $\{3/2^-[521]\otimes 2^+\}$ and $\{1/2^-[530]\}$ states. Furthermore, the decoupling parameter of $1/2^-[521]$ has an anomalous value. However, it has been calculated on the basis of the 1/2 and 3/2 levels, the only known levels in this band.
[i]Gareev *et al.* (1971) calculated about 26% admixture of $\{7/2^+[633]\otimes 0^-\}$ in this state.
[j]Komov *et al.* (1972) suggest an admixture of $\{5/2^-[523]\otimes 2^-\}$ in this state.
[k]Only other known level is 1/2 at 438.2 keV.
[l]Erskine *et al.* (1975) report many unassigned levels between 0.7 MeV and 1.4 MeV. In addition, Hoff (1975) identifies a $K=7/2$ band with level energies of 932, 988, and 1056 keV and spins 7/2, 9/2, and 11/2, respectively, having a tentative configuration $\{7/2^+[633]\otimes 0^+\}$. A 1040-keV level may be the bandhead of the $9/2^+[624]$ band.

TABLE XXXV. Intrinsic states of $Z=99$ odd-A nuclei.

$_{99}$Es	$A=249$[a]	251[b]	253[c]	$_{99}$Es	$A=249$[a]	251[b]	253[c]
$7/2^+[633]$	0	8.3 5.3 6.7	0 6.98	$9/2^+[624]$		(777.9) 6.8[a] 8.2	
$3/2^-[521]$		0 6.3	(50) 6.7	$1/2^+[400]$		(661)	
$1/2^-[521]$		411 6.8 1.0		$11/2^+$ $\{7/2^+[633]\otimes 2^+\}$		889.2 5.3 8.2	
$7/2^-[514]$		$(461.4)_\alpha$ 7.7	420				

[a]Schmorak (1981a): NDS.
[b]Schmorak (1981b): NDS; I. Ahmad *et al.* (1978): EC decay and (α,t).
[c]Schmorak (1981c): NDS; I. Ahmad *et al.* (1967): EC; Hoff, Hulet, *et al.* (1971): α decay.
[d]Calculated from the 9/2 and 13/2 level energies.

TABLE XXXVI. Intrinsic states of $N=141$ odd-A nuclei.

$N=141$	^{231}Th[a]	^{233}U[b]	$N=141$	^{231}Th[a]	^{233}U[b]
$5/2^+[633]$	0 6.0	0 5.8	$1/2^-[770]$	(3) 714[e] 6.1 −7.51	
$1/2^+[631]$[c]	247.6 7.1 0.16	398.6 (6.0) (−0.04) 6.6	$1/2^+[640]$	793.0 5.0[f] 0.06[f]	
$5/2^+[622]$	317.1 8.6	546.6 7.2	$3/2^+[642]$	(849) 7.2	
$7/2^-[743]$[d]	387.8_α 7.2	503.5_α 6.4	$3/2^-[501]$	875.5 7.8	
$7/2^+[624]$	(510.9)		$3/2^-$ $\{3/2^+[631]\otimes 0^-\}$	619.6	

TABLE XXXVI. Intrinsic states of $N=141$ odd-A nuclei.

$N=141$	^{231}Th[a]	^{233}U[b]	$N=141$	^{231}Th[a]	^{233}U[b]
$5/2^-[752]$[d]	(185.7) 2.8	298.9 3.1	$5/2^-$ $\{5/2^-[752]\otimes 0^+\}$	623.9 1.4	
$3/2^+[631]$[c]	221.4 3.9	311.9 5.7 7.3	$1/2^+$ $\{5/2^+[633]\otimes 2^+\}$	687.6 6.1 0.15	
$1/2^-[501]$	554.7 6.8 0.92	572	$1/2^+$ $\{1/2^+[631]\otimes 0^+\}$	820.5[g] (6.0) (0.04)	
$3/2^-[761]$	590.8 7.7		$3/2^-$ $\{5/2^+[633]\otimes 1^-\}$	936.3	
$5/2^-[503]$	684.5 5.1		$3/2^+$ $\{3/2^+[631]\otimes 0^+\}$	960.8	
$5/2^-$ $\{5/2^+[633]\otimes 0^-\}$		(748) 6.0			
Other levels	h	i			

[a]Schmorak (1983): NDS; White *et al.* (1987): (n,γ), $(n,\gamma e)$, (d,p); White *et al.* (1979): (n,γ); Vaňo *et al.* (1975): α decay; Elze *et al.* (1969): (^{3}He,α); Boyno *et al.* (1970): (d,t); Grotdal *et al.* (1972): (d,p), (d,t).

[b]Ellis (1978): NDS; Albridge *et al.* (1961), Schultze and Ahlf (1962), Bisgård *et al.* (1963): β decay; Friedman *et al.* (1974): (p,t); Thompson *et al.* (1976): (d,d'); Johnson *et al.* (1978): (d,t), (^{3}He,α); Ellis *et al.* (1979): α decay; Newton (1958): Coul.; Hardt *et al.* (1983): $(\alpha,3n)$.

[c]The $1/2^+[631]$ and $3/2^+[631]$ bands are expected to mix by Coriolis coupling.

[d]The $7/2^-[743]$ and $5/2^-[752]$ bands are strongly Coriolis mixed. From the (p,t) reaction data in ^{233}U, Friedman *et al.* (1974) estimate the mixing to be $\sim 25\%$.

[e]The 1/2 level lies at 833 keV.

[f]Calculated from the 1/2, 3/2, and 7/2 levels.

[g]White *et al.* (1987) pointed out some admixture of the $K^\pi=0^+$, β vibration built on the $1/2^+[631]$ Nilsson state in three rotational bands, which lie within 140 keV of each other. This fragmentation is theoretically unexpected. Many other states are expected to have vibrational admixture. In particular, the states having large admixtures are $5/2^+[622]$ 47% with $\{5/2^+[633]\otimes 0^+\}$ 46%; $\{5/2^-[752]\otimes 0^+\}$ 76% with $5/2^-[503]$ 13%, and $\{3/2^+[631]\otimes 0^+\}$ 73% with $3/2^+[642]$ 18%.

[h]Elze *et al.* (1969) had proposed the bandhead of the $1/2^+[631]$ band at 75 keV in the (^{3}He,α) reaction, but White *et al.* (1979, 1987) reassigned the energy of this band at 247.6 keV. The bandhead of $5/2^-[503]$ was earlier proposed by Boyno *et al.* (1970) at 876 keV, which is now assigned at 684.5 keV.

[i]The configurations 5/2, $5/2^-[503]$ and 3/2, $3/2^-[501]$ are tentatively assigned to levels at 916 and 1016 keV by Johnson *et al.* (1978). They also report many unassigned levels between 0.5 MeV and 1.2 MeV. In addition, three levels at 819, 1824, and 2070 keV are populated in the (p,t) reaction with $l=0$ transitions. These may belong to the $\{7/2^-[743]\otimes 0^+\}$ states.

TABLE XXXVII. Intrinsic states of $N=143$ odd-A nuclei.

$N=143$	^{233}Th[a]	^{235}U[b]	^{237}Pu[c]
$7/2^-[743]$	(6.07)	0 5.1	0 5.3 ≥ 7.1
$1/2^+[631]$	0 6.6 -0.15	$0.1_{iso,\alpha}$ 6.0 -0.28	$145.6_{iso,\alpha}$ 6.2 -0.47 ≥ 7.1
$5/2^+[622]$	6.04 6.3	129.3 6.0	280.2 5.8 6.0

TABLE XXXVII. (*Continued*).

$N=143$		^{233}Th[a]			^{235}U[b]			^{237}Pu[c]	
$7/2^+[624]$	5.3	278		7.1	445.7[e]			473.5	6.7
$9/2^-[734]$				5.8	821.8				
$7/2^+[613]$								908.8	6.4
$1/2^+[620]$ + $\{5/2^+[622]\otimes 2^+\}$	6.4	(583.9)	0.45						
$5/2^+[633]$[d]	2.5	262.2		4.9	332.8		4.4	407.8	6.8
$3/2^+[631]$	7.1	335.9		6.6	393.5		6.8	370.4	7.3
$5/2^-[752]$		(478.4)		5.4	632.9		5.8	(655.3)	7.2
$1/2^-[501]$ $+1/2^-[770]$	(6.0)	(539.6)	(1.58)		659.0		6.8	(545)	1.27
$3/2^-[501]$ $+3/2^-[761]$		(924.7)			805.7			(1014)	
$5/2^-[503]$								(852)	
$3/2^-[761]$[f]	8.5	(741.3)		4.3	1039.2				
$3/2^-$ $\{7/2^-[743]\otimes 2^+\}$	5.3	572.7		5.3	637.9				
$1/2^-$ $\{1/2^+[631]\otimes 0^-\}$				5.7	761.1	−0.48			
$1/2^+$ $\{1/2^+[631]\otimes 0^+\}$	6.1	(713.6)	−0.56	5.9	769.3	−0.42		800	
$1/2^+$ $\{5/2^+[622]\otimes 2^+\}$				6.2	843.9[g]	0.14			
$5/2^+$ $\{5/2^+[622]\otimes 0^+\}$	6.1	(711.2)			905.3				
$11/2^-$ $\{7/2^-[743]\otimes 2^+\}$				5.1	920.8				

TABLE XXXVII. (*Continued*).

$N=143$	^{233}Th[a]	^{235}U[b]	^{237}Pu[c]
3/2$^+$ ({1/2$^+$[631]⊗2$^+$})		968.5	
7/2$^-$ {7/2$^-$[743]⊗0$^+$}		1063	
Other levels	h	i	

[a]Hoekstra and Wapstra (1969): ^{233}Th β decay; von Egidy *et al.* (1972): (d,p), (n,γ); Kern and Due (1974), Jeuch *et al.* (1979): (n,γ); Grotdal *et al.* (1972): (d,p).
[b]Schmorak (1983): NDS; Braid *et al.* (1970): (d,p), (d,t); Elze and Huizenga (1969): (^{3}He,α); Baranov *et al.* (1963), Cline (1968): α decay; Rickey *et al.* (1972): (t,p), (d,p), (d,t), (n,γ), (d,d'); Thompson *et al.* (1976): (d,d'); Almeida *et al.* (1979): (n,γ); Simon *et al.* (1980), de Bettencourt *et al.* (1986): Coul.
[c]Ellis-Akovali (1986): NDS; I. Ahmad *et al.* (1975): α decay and EC; Friedman *et al.* (1974): (p,t); Grotdal *et al.* (1973): (d,t).
[d]The 5/2$^+$[633] and 7/2$^+$[624] bands originating from the $g_{9/2}$ orbital are expected to mix strongly.
[e]Thompson *et al.* (1976) and Almeida *et al.* (1979) have interpreted this band as the {7/2$^-$[743]⊗0$^-$} band.
[f]Strong Coriolis coupling with the 1/2$^-$[770] and 1/2$^-$[750] bands is expected. An admixture of the 3/2$^-$[761] band is also suggested by the particle-rotor-model calculations.
[g]Rickey *et al.* (1972) assign the 843.7-keV level as the bandhead of the 3/2$^+$[622] band.
[h]Grotdal *et al.* (1972) have suggested the levels at 1097, 1125, 1150, and 1215 keV to be the $I=1/2$, 3/2, 5/2, and 7/2 members of the 1/2$^+$[620] rotational band. Von Egidy *et al.* (1972) observed these levels at 1101, 1130, 1152, and 1219 keV. Kern and Due (1974) have suggested the following I^π values to some levels: 611 keV (3/2$^+$,5/2$^+$), 692 keV (3/2$^+$,5/2$^+$), 839 keV (3/2$^+$), 1050 keV (3/2$^+$), 1151 keV (3/2$^+$), and 1185 keV (3/2$^+$). Many other levels are seen above 500 keV by the (d,p) reaction (von Egidy *et al.*, 1972) and remain unassigned. Besides the four vibrational states given here, Jeuch *et al.* (1979) have also tentatively assigned three more vibrational bands at 682 keV {1/2$^+$[631]⊗0$^-$}, 815 keV {1/2$^+$[631]⊗2$^+$}, and 842 keV {5/2$^+$[633]⊗2$^+$}.
[i]Rickey *et al.* (1972) have suggested additional bandheads with tentative configurations for the following levels: 507.7 keV 5/2$^+$; 640.5 keV 1/2$^+$; 970.0 keV 7/2$^+$; 992.8 keV 1/2$^+$; 1116.2 keV 5/2$^+$; 1194.3 keV 1/2$^-$; 1236 keV 7/2$^+$; 1242.3 keV 3/2$^-$; 1272.6 keV 1/2$^+$; 1382.5 keV 1/2$^-$; 1412.8 keV 3/2$^+$; and 1438 keV 9/2$^+$. Of these, only the 1194.3-keV level has the same spin-parity in the "Adopted Levels" in the recent Nuclear Data Sheets (Schmorak, 1983). Rickey *et al.* (1972) assign it as the bandhead for the 1/2[761] configuration. The 1116.2-keV level is assigned the same spin, but opposite parity. None of the other levels have been confirmed in more recent investigations.

TABLE XXXVIII. Intrinsic states of $N=145$ odd-A nuclei.

$N=145$		^{237}U[a]			^{239}Pu[b]		^{241}Cm[c]
1/2$^+$[631]	6.4 7.1	0	−0.41	6.3	0	−0.58	0
5/2$^+$[622]	6.3	160.0$_\alpha$		6.4 7.1	285.5$_\alpha$	6.0	
7/2$^+$[624]	6.2	426.2		5.9	511.8	5.8	
1/2$^-$[761]				6.5	(3) (990)[d]	−2.38	

TABLE XXXVIII. (*Continued*).

$N=145$		$^{237}U^{a}$			$^{239}Pu^{a}$		$^{241}Cm^{c}$
$1/2^+$ $\{5/2^+[622]\otimes 2^+\}$ $+1/2^+[620]$	6.3	(846.9)	0.33				
$1/2^+[620]$		$(1110)^{e}$		6.0	(1214)	0.06	
$7/2^+[613]$		(9) (1126)			(9) (1233)		
$3/2^+[622]$				5.6	(1261)		
$7/2^-[743]$	4.7	274.0		4.8 6.3	(391.6)	8.6	
$3/2^+[631]$	6.7	664.3					
$5/2^+[633]$		(832.5)					
$1/2^-[501]$	(6.0) 5.8	865.0	(1.13)				
$5/2^-[752]$		(15) (1259)					
$3/2^-[761]$		(15) (1849)					
$13/2^+[606]$		1888					
$1/2^-$ $\{1/2^+[631]\otimes 0^-\}$ $+1/2^-[501]$	4.7 6.5	540.6^{f}	0.02	5.1	469.8	0.47	
$1/2^-$ $\{1/2^+[631]\otimes 0^-\}$ $+1/2^-[501]$	6.0 7.4	734.3^{f}	0.32				
$1/2^+$ $\{1/2^+[631]\otimes 0^+\}$	5.2	(905.7)	-0.05				
Other levels		g			h		

[a]Ellis-Akovali (1986): NDS; von Egidy *et al.* (1970): (^{3}He,α); Braid *et al.* (1965): (d,p); Boyno *et al.* (1970), Erskine (1972): (d,t); von Egidy, Cizewski, *et al.* (1979): (n,γ).
[b]Ewans *et al.* (1959), Davies and Hollander (1965): β decay; Baranov *et al.* (1966): α decay; Porter *et al.* (1972): EC; Grotdal *et al.* (1973): (d,p), (d,d'); Thompson *et al.* (1976): (d,d'); Hardt *et al.* (1983): ($\alpha,3n$).
[c]Table of Isotopes (Lederer and Shirley, 1978): α decay.
[d]The 1/2 level of this band lies at 1017 keV.
[e]Calculations of Gareev *et al.* (1971) suggest a large admixture of the $\{5/2^+[622]\otimes 2^+\}$ vibration.
[f]There is no clear indication about which of the two levels is an octupole vibrational state. This state is

TABLE XXXVIII. (*Continued*).

observed in ^{235}U at 761 keV and in ^{239}U at 815 keV. Therefore, according to the systematics, the 734-keV level may be the octupole state.
[g]Levels observed at 1192 and 1235 keV in the (d,p) reaction may possibly belong to the $3/2^+[622]$ band.
[h]A number of unassigned levels between 0.7 MeV and 1 MeV are reported by Thompson *et al.* (1976). Baranov *et al.* (1966) also report four unassigned levels at 745, 754, 761, and 810 keV, which are probably collective in nature.

TABLE XXXIX. Intrinsic states of $N=147$ odd-A nuclei.

$N=147$	^{239}U[a]			^{241}Pu[b]			^{243}Cm[c]		
$5/2^+[622]$	0	6.1		0	6.0 6.0		0	6.0	
$7/2^+[624]$	(9) 226.3	6.9		174.9^{d}_{α}	6.3 6.1		(133)	3.4	
$1/2^+[620]$	(687.9)	6.5	0.42	755.1	5.5	−0.13			
$1/2^-[761]$	739.4[e]	4.9	−0.55						
$3/2^+[622]$	(853.2)	6.8		(936)[j]					
$7/2^+[613]$				(9) 800					
$1/2^-[750]$	1194.6	(6.0)	(0.59)						
$1/2^+[631]$	133.8	6.8	−0.41	161.6	6.7	−0.55	87.4_{iso}	(6.0)[f]	(−0.63)[f]
$7/2^-[743]$	(292.6)	4.0[g]		(11) 444	4.5[h]		(15) (530)		
$5/2^+[633]$	(694.7)			(9) 1181					
$3/2^+[631]$	(726.1)	6.2					(5) 798	5.9[i]	
$1/2^-[501]$ $+(1/2^-[750])$	(932.9)	6.9	0.39	(844)[j]			729	6.7	1.0
$5/2^-[503]$							(1136)		
$5/2^-[752]$				(15) 1868					

TABLE XXXIX. (*Continued*).

$N=147$		^{239}U[a]			^{241}Pu[b]			^{243}Cm[c]	
$5/2^-$ $\{5/2^+[622]\otimes 0^-\}$		539.3							
$1/2^-$ $\{1/2^+[631]\otimes 0^-\}$ $+(1/2^-[501])$	4.9	815.2	−0.42		(965.1)				
$3/2^+$ $\{1/2^+[631]\otimes 2^+\}$	4.5	965.6							
$5/2^-$ $(\{1/2^+[631]\otimes 2^-\})$		(1018.6)							
$5/2^+$ $\{5/2^+[622]\otimes 0^+\}$		1062.5							
$1/2^+$ $\{1/2^+[631]\otimes 0^+\}$	5.4	1155.1	−0.26						
Other levels		k			l				

[a]Schmorak (1983): NDS; Sheline *et al.* (1966): (d,p), (n,γ); Bollinger and Thomas (1972), Börner *et al.* (1978), Chrien and Kopecky (1984): (n,γ); Yates, Ahmad, *et al.* (1975), Erskine (1978): (d,p).
[b]Ellis-Akovali (1985): NDS; Baranov and Shatinskii (1975): α decay; Parekh *et al.* (1981): β decay; Elze and Huizenga (1971): (d,t), $(^3He,\alpha)$; Braid *et al.* (1972): (d,p), (d,t).
[c]Ellis-Akovali (1981a): NDS; Braid *et al.* (1971): (d,t); Yates, Ahmad, *et al.* (1975): τ measurement.
[d]The bandhead $7/2^+$ was not observed by Braid *et al.* (1972), and neither the $7/2^+$ nor the $9/2^+$ levels were seen by Elze and Huizenga (1971).
[e]Erskine (1978) suggested a 1/2[750] configuration for this band. However, Börner *et al.* (1978) and Chrien and Kopekcy (1984) assign the 1/2[750] configuration to the 1195-keV $1/2^-$ and 1223-keV $3/2^-$ set of levels. Anomalously low decoupling parameters for both the 739-keV and the 1195-keV $K^\pi=1/2^-$ bands suggest admixture of both the [761] and [750] configurations in these two bands.
[f]Calculated from the 1/2 and 3/2 levels only. The 9/2 level proposed at 298 keV does not fit into the general trend.
[g]Value calculated from the transition between $11/2^-$ and $7/2^-$ states.
[h]Value calculated from the 11/2 and 15/2 levels.
[i]Value calculated from the 5/2 and 9/2 level energies.
[j]Gareev *et al.* (1971) report considerable admixture of the octupole vibration $\{1/2^+[631]\otimes 0^-\}$ in the $1/2^-[501]$ state. They also report about 40% admixture of $\{7/2^+[624]\otimes 2^-\}$ in the $3/2^+[622]$ state.
[k]Erskine (1978) assigns a $K^\pi=2^-$ vibrational band built upon the $5/2^+[622]$ state to the levels at 1225.5, 1242.0, and 1295.2 keV.
[l]Braid *et al.* (1972) observed many levels between 777 keV and 1826 keV, which remain unassigned.

TABLE XL. Intrinsic states of $N=149$ odd-A nuclei.

$N=149$		^{243}Pu[a,f]			^{245}Cm[b]			^{247}Cf[c]	
$7/2^+[624]$	6.5	0		6.1 6.3	0		6.1	0	
$9/2^-[734]$	4.7	402.4_α		5.0	388.2_α		4.7	480.4_α	
$1/2^+[620]$	7.0	625.6	0.33	6.9	741.0	0.37			

TABLE XL. (*Continued*).

$N=149$	^{243}Pu[a,f]			^{245}Cm[b]			^{247}Cf[c]		
7/2$^+$[613]	(9) 626			(722)	6.7				
1/2$^-$[761]	(3) 790.7[d]	7.1	−4.91	(3) 980	(6.0)	(−2.92)			
3/2$^+$[622]	813.8	6.3		908	6.8				
9/2$^+$[615]	(11) (1044)								
5/2$^+$[622]	287.4	6.5		252.9	6.1 6.5	6.9	383.2	6.3	
1/2$^+$[631]	383.6	6.9	−0.60	356.0	6.7	−0.72 8.0			
7/2$^-$[743]				(643.5)	6.5		678.0	6.7	
1/2$^-$[501]	905.6	(6.0)	(1.36)	913	7.2	1.0			
3/2$^+$[631][e] + {1/2$^+$[631]⊗2$^+$}	(5) 981.0	6.2		(5) 995	5.5				
5/2$^-$[503]	1212.8			1271					
3/2$^-$ {7/2$^+$[624]⊗2$^-$}	703.9			633.7	5.6	6.9			
Other levels	g								

[a]Ellis-Akovali (1981a): NDS; Fields *et al.* (1971): α decay; Casten *et al.* (1976): (d,p), (d,t), (n,γ); Braid *et al.* (1972): (d,p).
[b]Ellis-Akovali (1981a): NDS; Braid *et al.* (1971): (d,p), (d,t); Baranov *et al.* (1977): α decay; Ahmad, Sharma, and Sjoblom (1976): EC decay; Bunker *et al.* (1967): β decay.
[c]Ellis-Akovali (1981b): NDS; I. Ahmad *et al.* (1973): α decay.
[d]The 1/2 level lies at 873.9 keV. The parameters are calculated from the levels at spins 1/2, 3/2, and 7/2.
[e]Calculations of Gareev *et al.* (1971) suggest this admixture. The inertia parameter in both cases is calculated from the 5/2 and the 9/2 energy levels.
[f]Theoretical calculations with phonon-quasiparticle mixing in this nucleus are presented by Komov *et al.* (1972).
[g]Braid *et al.* (1972) report many levels between 1198 and 1808 keV, which remain unassigned.

TABLE XLI. Intrinsic states of $N=151$ odd-A nuclei.

$N=151$	^{245}Pu[a]	^{247}Cm[b]	^{249}Cf[c]	^{251}Fm[d]
$9/2^-[734]$	0 5.6	0 5.6	0 5.7 6.7	0 4.3
$1/2^+[620]$	309 6.8[e] 0.42[e]	403.6_{α} 6.5 0.51	416.6_{α}	$(550)_{\alpha}$
$7/2^+[613]$[f]	(9) (328)	(9) (439)	443.0 6.1 7.2	(397) 4.8
$3/2^+[622]$	(578) 7.6	668 6.2		
$1/2^-[761]$	(3) (640) (6.0)[g] (−2.83)[g]	(3) 784 5.4[h] −2.74[h]		
$9/2^+[615]$	(11) 805	(11) 687	1007.9 6.6	
$5/2^+[622]$	(9) 249	227_{iso} 5.6 6.3	145.0^{i}_{iso} 6.1 7.3	$(190)_{\text{iso}}$ 6.7
$7/2^+[624]$[f]		285.0 6.6	379.5 6.4 6.2	
$1/2^+[631]$		(506) 5.3[j] −0.13[j]		
$1/2^-[501]$		958 7.2 1.0		
$3/2^+[631]$		(5) 1079 6.4[k]		
$5/2^-[503]$ + $\{9/2^-[734]\otimes 2^+\}$		1283[l]		
$13/2^-$ $\{9/2^-[734]\otimes 2^+\}$			668 5.5	
$5/2^-$ $\{9/2^-[734]\otimes 2^+\}$			813.2 5.6	
$11/2^+$ $\{9/2^-[734]\otimes 1^-\}$			920 5.5	
$13/2^+$ $\{9/2^-[734]\otimes 2^-\}$			1063 5.5	
$15/2^+$ $\{9/2^-[734]\otimes 3^-\}$			1078 5.9	

TABLE XLI. (*Continued*).

$N=151$	^{245}Pu[a]	^{247}Cm[b]	^{249}Cf[c]	^{251}Fm[d]
7/2$^-$ {3/2$^+$[622]⊗2$^-$}			1218.5[m] 5.5 5.5	
7/2$^+$ {9/2$^-$[734]⊗1$^-$}			1415 5.3	
Other levels		n	o	

[a]Ellis-Akovali (1981a): NDS; Chasman *et al.* (1977): (d,p).
[b]Ellis-Akovali (1981b): NDS; Braid *et al.* (1971): (d,p), (d,t); Orth *et al.* (1967): β decay; Chetham-Strode *et al.* (1968): α decay.
[c]Schmorak (1981a): NDS; I. Ahmad *et al.* (1967): α decay; Yates, Chasman, *et al.* (1975): (d,d'); Ahmad, Sjoblom, and Fields (1976): EC.
[d]Schmorak (1981b): NDS; Eskola *et al.* (1970), Dittner *et al.* (1971): α decay.
[e]Values calculated from the 1/2, 5/2, and 7/2 level energies.
[f]Gareev *et al.* (1971) predict considerable mixing ($\sim$30%) of the 7/2$^+$[613] and the 7/2$^+$[624] states.
[g]Values calculated from the 3/2 and 7/2 levels only.
[h]The 1/2 level energy is unknown. Values are calculated from the 1/2, 3/2, and 7/2 levels. Chasman *et al.* (1977) had assigned this as 1/2$^-$[750]. However, a large negative decoupling parameter suggests that it must be the 1/2$^-$[761] state.
[i]Yates, Chasman, *et al.* (1975) show a large vibrational admixture in this state from the 5/2$^+$ {9/2$^-$[734]⊗2$^-$} phonon.
[j]Values calculated from the 1/2, 3/2, and 7/2 level energies.
[k]Values calculated from the 5/2 and 9/2 levels.
[l]Calculations of Gareev *et al.* (1971) predict this state to be about 50% vibrational.
[m]In EC decay studies, this state is interpreted as having a large three-quasiparticle character $\{7/2^+[633]_p, 3/2^-[521]_p, 3/2^+[622]_n\}$.
[n]Braid *et al.* (1971) observe many other levels between 309 keV and 1512 keV, which remain unassigned.
[o]A number of unassigned levels between 1 MeV and 1.9 MeV are reported by Yates, Chasman *et al.* (1975). I. Ahmad *et al.* (1967) tentatively assign a level at 551 keV as the 1/2$^+$[631] state. They also observe levels at 1238.0 keV (5/2, 7/2) and 1304.3 keV (5/2, 7/2, 9/2) in EC studies.

TABLE XLII. Intrinsic states of $N=153$ and $N=155$ odd-A nuclei.

$N=153$	^{249}Cm[a]	^{251}Cf[b]	$N=155$	^{253}Cf[c]
1/2$^+$[620]	0 6.6 0.33	0 6.4 0.29 6.2	7/2$^+$[613]	0 6.8
7/2$^+$[613]	$48.7_{\alpha,\text{iso}}$ 6.8	106.3_{α} 6.7	9/2$^+$[615]	241.0_{α} 7.3
3/2$^+$[622]	208 6.8	177.7 6.8 $\sim$5.7		
9/2$^+$[615]	(220) 7.3			
11/2$^-$[725]		370.4_{iso} 5.5		

TABLE XLII. (*Continued*).

$N=153$	^{249}Cm[a]	^{251}Cf[b]	$N=155$	^{253}Cf[c]
$1/2^-[761]$[d]	(3) (470.2)[e] 3.6 −3.24			
$3/2^-[752]$[d]	772.7 9.2			
$9/2^-[734]$		434.3 7.2		
$5/2^+[622]$	529.6 7.0	544.1 6.6		
$1/2^-[501]$	917.5 8.4 0.80			
Other levels	f			

[a]Schmorak (1981a): NDS; Bemis and Halperin (1968): α decay; Hoff, Davidson *et al.* (1982): (n,γ); Braid *et al.* (1971): (d,p).
[b]Schmorak (1981b): NDS; Ahmad *et al.* (1970): EC; Ahmad *et al.* (1971), Ahmad and Milsted (1975): α decay; Liu *et al.* (1984): β decay.
[c]Schmorak (1981c): NDS; Asaro and Perlman (1967), Ahmad and Horwitz (1982): α decay.
[d]Considerable Coriolis mixing is expected between the $1/2^-[761]$ and $3/2^-[752]$ states (Hoff, Davidson *et al.*, 1982). Gareev *et al.* (1971) also suggest vibrational admixtures in these states.
[e]The 1/2 level lies at 494.5 keV.
[f]The $7/2^+[613]$ band and the 1/2 level of the $1/2^-[761]$ band were not seen in the (d,p) reaction. A number of unassigned levels between 0.8 and 1.3 MeV are reported by Hoff, Davidson *et al.* (1982).

TABLE XLIII. Decoupling parameter values for $K=1/2$ states in odd-Z actinide nuclei. Empirical values shown in parentheses are calculated by assuming $\hbar^2/2\mathfrak{I}=6.0$ keV.

State configuration	Calculated[a] A	a	Empirical Nucleus	a	Nucleus	a
$1/2^-[530]$	230	−2.21	^{229}Ac	(−0.75)	^{235}Np	−2.10
	238	−2.34	^{231}Ac	(−1.33)	^{237}Np	−1.67
	242	−2.49	^{229}Pa	−1.58	^{239}Np	−1.71
	248	−2.64	^{231}Pa	−1.49	^{241}Am	(−1.85)
			^{233}Pa	−1.37	^{249}Bk	−1.76
			^{235}Pa	−0.35	^{251}Bk	(−1.88)
			^{237}Pa	(−1.25)		
$1/2^+[400]$	230	+0.43	^{229}Ac	+1.22	^{237}Np	+1.08
	238	+0.56	^{231}Ac	(+1.11)	^{239}Np	+0.76
	242	+0.71	^{231}Pa	(+0.72)	^{241}Am	(+0.67)
	248	+0.48	^{233}Pa	+0.67	^{247}Bk	(+0.72)
			^{235}Pa	(+0.89)	^{249}Bk	+0.69
			^{237}Pa	(+0.94)		

TABLE XLIII. (*Continued*).

State configuration	Calculated[a] A	a	Empirical Nucleus	a	Nucleus	a
$1/2^-[521]$	242	+1.34	^{247}Bk	+0.89	^{251}Bk	(+0.11)
	248	+1.37	^{249}Bk	(+0.02)	^{251}Es	+1.00

[a]The Nilsson parameters used for calculation are $\kappa_{\text{proton}}=0.059$, $\mu_{\text{proton}}=0.639$, $\kappa_{\text{neutron}}=0.0635$, $\mu_{\text{neutron}}=0.346$ (for $A=230$); $\kappa_{\text{proton}}=0.0577$, $\mu_{\text{proton}}=0.650$, $\kappa_{\text{neutron}}=0.0635$, $\mu_{\text{neutron}}=0.325$ (for $A\geq 238$). The deformation parameters used are $\epsilon_2=0.17$, $\epsilon_4=-0.06$ (for $A=230$); $\epsilon_2=0.20$, $\epsilon_4=-0.04$ (for $A=238$); $\epsilon_2=0.22$, $\epsilon_4=-0.02$ (for $A=242$); $\epsilon_2=0.24$, $\epsilon_4=0.0$ (for $A=248$).

TABLE XLIV. Decoupling parameter values for $K=1/2$ states in odd-N actinide nuclei. Empirical values shown in parentheses are calculated by assuming $\hbar^2/2\mathfrak{J}=6.0$ keV.

State configuration	Calculated[a] A	a	Empirical Nucleus	a	Nucleus	a
$1/2^-[501]$	230	+1.01	^{227}Ra	+0.87	^{243}Pu	(+1.36)
	238	+1.10	^{231}Th	+0.92	^{243}Cm	+1.0
	242	+1.06	^{233}Th	(+1.58)	^{245}Cm	+1.0
	248	+1.09	^{237}U	(+1.13)	^{247}Cm	+1.0
			^{239}U	+0.39	^{249}Cm	+0.80
			^{237}Pu	+1.27		
$1/2^-[761]$	230	−4.42(−1.61)	^{227}Ra	+1.83	^{245}Cm	−2.92
	238	−4.42(−1.40)	^{239}Pu	−2.38	^{247}Cm	−2.74
	242	−4.59(−1.64)	^{243}Pu	−4.91	^{249}Cm	−3.24
	248	−4.47(−2.18)	^{245}Pu	(−2.83)		
$1/2^+[631]$	230	−0.04(−0.76)	^{231}Th	+0.16	^{239}Pu	−0.58
	238	−0.06(−0.84)	^{233}Th	−0.15	^{241}Pu	−0.55
	242	−0.13(−0.91)	^{233}U	(−0.04)	^{243}Pu	−0.60
	248	−0.18(−0.94)	^{235}U	−0.28	^{243}Cm	(−0.63)
			^{237}U	−0.41	^{245}Cm	−0.72
			^{239}U	−0.41	^{247}Cm	−0.13
			^{237}Pu	−0.47		
$1/2^+[620]$	230	−0.81(+0.08)	^{233}Th	+0.45	^{245}Pu	+0.42
	238	−0.83(+0.15)	^{237}U	+0.33	^{245}Cm	+0.37
	242	−0.79(+0.16)	^{239}U	+0.42	^{247}Cm	+0.51
	248	−0.76(+0.16)	^{239}Pu	+0.06	^{249}Cm	+0.33
			^{241}Pu	−0.13	^{251}Cf	+0.29
			^{243}Pu	+0.33		
$1/2^-[750]$	238	+4.65(+2.34)	^{239}U	(+0.59)		
$1/2^-[770]$	230	−7.37	^{231}Th	−7.51		
$1/2^+[640]$	230	−3.13(−0.96)	^{231}Th	+0.06		

[a]Parameters used for calculation are given in Table XLIII. The calculated values in parentheses are obtained by using an improved set of parameters: $\kappa_{\text{proton}}=0.05$, $\mu_{\text{proton}}=0.76$, $\kappa_{\text{neutron}}=0.05$, $\mu_{\text{neutron}}=0.45$ for all A.

TABLE XLV. Experimental data on $K=0^-$, 0^+, and 2^+ vibrational states in actinides. Energies are in keV. Vibrational states enclosed in braces are probably more admixed than others. A star (*) indicates an estimated value from higher band members.

	Base single-particle state				Octupole vibration $K=0^-$			Beta vibration $K=0^+$			Gamma vibration $K=2^+$		
Nucleus	$\Omega^\pi[Nn_3\Lambda]$	Bandhead energy	A (keV)	a	$2K^\pi$ bandhead energy	A (keV)	a	$2K^\pi$, bandhead energy	A (keV)	a	$2K^\pi$, bandhead energy	A (keV)	a
^{231}Th	$5/2^+[633]$	0.0	6.0								1^+, 687.6	6.1	0.15
	$1/2^+[631]$	247.6	7.1	0.16				1^+, 820.5	(6.0)	(0.04)			
	$5/2^-[752]$	(185.7)	2.8					5^-, 623.9	1.4				
	$3/2^+[631]$	221.4	3.9		3^-, 619.6			3^+, 960.8					
^{233}Th	$1/2^+[631]$	0.0	6.6	−0.15				1^+, (713.6)	6.1	−0.56			
	$5/2^+[622]$	6.04	6.3					5^+, (711.2)	6.1		{1^+, 583.9	6.4	0.45}
	$7/2^-[743]$	6.07									3^-, 572.7	5.3	
^{233}U	$5/2^+[633]$	0.0	5.8		5^-, (748)	6.0							
^{235}U	$7/2^-[743]$	0.0	5.1					7^- 1063			[3^-, 637.9	5.3	
											11^-, 920.8]	5.1	
	$1/2^+[631]$	0.1	6.0	−0.28	1^-, 761.1	5.7	−0.48	1^+, 769.3	5.9	−0.42	3^+, 968.5		
	$5/2^+[622]$	129.3	6.0					5^+, 905.3			1^+, 843.9	6.2	0.14
	$5/2^+[633]$	332.8	4.9					{5^+, 507.7}					
^{237}U	$1/2^+[631]$	0.0	6.4	−0.41	{1^-, 734.3	6.0	0.32}	1^+, (905.7)	5.2	−0.05			
	$5/2^+[622]$	160.0	6.3								{1^+, (846.9)	6.3	0.33}
^{239}U	$5/2^+[622]$	0.0	6.1		5^- 539.3			5^+, 1062.5					
	$1/2^+[631]$	133.8	6.8	−0.41	{1^-, 815.2	4.9	−0.42}	1^+, 1155.1	5.4	−0.26	3^+, 965.6	4.5	
^{235}Np	$5/2^+[642]$	0.0						5^+, 834					
^{237}Pu	$1/2^+[631]$	145.6	6.2	−0.47				1^+, 800					
^{239}Pu	$1/2^+[631]$	0.0	6.3	−0.58	{1^-, 469.8	5.1	+0.47}						
^{243}Pu	$1/2^+[631]$	383.6	6.9	−0.60							{3^+, 950*	6.2}	
^{241}Am	$5/2^-[523]$	0.0	5.8					5^-, (952)					
^{245}Cm	$1/2^+[631]$	356.0	6.7	−0.72							{3^+, 967*	5.5}	
^{247}Cm	$9/2^-[734]$	0.0	5.6								{5^-, 1283}		
^{249}Cf	$9/2^-[734]$	0.0	5.7								[13^-, 668	5.5	
											5^-, 813.2]	5.6	
^{251}Es	$7/2^+[633]$	0.0									11^+, 889.2	5.3	

VIII. ENERGY SYSTEMATICS OF INTRINSIC STATES IN THE ACTINIDE REGION

A. Octupole deformed nuclei

Empirical evidence for the presence of octupole deformation in the actinides is much more substantial than that in the rare earths. A variety of experimental data and theoretical studies support the existence of octupole as well as quadrupole deformation for nuclei in the mass range $220 \leq A \leq 230$. The closely lying $g_{9/2}$ and $j_{15/2}$ neutron orbitals and the $f_{7/2}$ and $i_{13/2}$ proton orbitals which are also close to the Fermi surface in this mass region form the basis for the existence of octupole deformation.

The criteria, which suggest the existence of stable octupole deformation in odd-A nuclei in the narrow mass region centered at approximately ^{225}Ac, have been summarized in Sec. III.A.3.

Detailed experimental data on some 12 nuclei, summarized in Tables XX and XXX, are interpreted in terms of the quadrupole-octupole single-particle model. Furthermore, additional data on these 12 nuclei and on other nuclei in this region can be anticipated.

In view of the growing body of data now available and expected, it is both challenging and important to define more explicitly in the nuclear periodic table the actinide region where quadrupole-octupole deformation occurs.

1. Systematics of ground-state spin and parity

One possible way to define the actinide region of quadrupole-octupole shape is to locate the nuclei in that region whose experimental ground-state spins are those predicted by a quadrupole-octupole single-particle model and are, in general, not consistent with the quadrupole Nilsson model only.

A summary of the ground-state spins and parities of odd-A nuclei beyond ^{208}Pb and in the region of interest is given in Fig. 32. These spins are taken from the data compiled in this paper and from the Table of Isotopes (Lederer and Shirley, 1978). In addition, the $(9/2^+)$ assignment for ^{219}Th can be made on the basis of the hindrance factor (HF)=2.7 in the alpha decay to the known $9/2^+$ ground state of ^{215}Ra; the large ground-state→ground-state HF's for the alpha decay of ^{221}Th and ^{219}Ra to known $9/2^+$ ground states imply that these ground-state spins are not $9/2^+$. Finally, the 5/2 ground spin of ^{221}Fr has been shown (Coc *et al.*, 1985) to be the anomalous bandhead of a $K^\pi = 1/2^-$ band (Sheline, 1988).

The spins of Fig. 32 can be compared with the calculations (Leander and Sheline, 1984) of the parity-mixed proton and neutron orbitals (Figs. 10 and 11) expected for a quadrupole-octupole deformed system. Since the quadrupole and octupole deformations are both varying quite rapidly and independently, we really need a three-dimensional diagram of octupole deformation versus

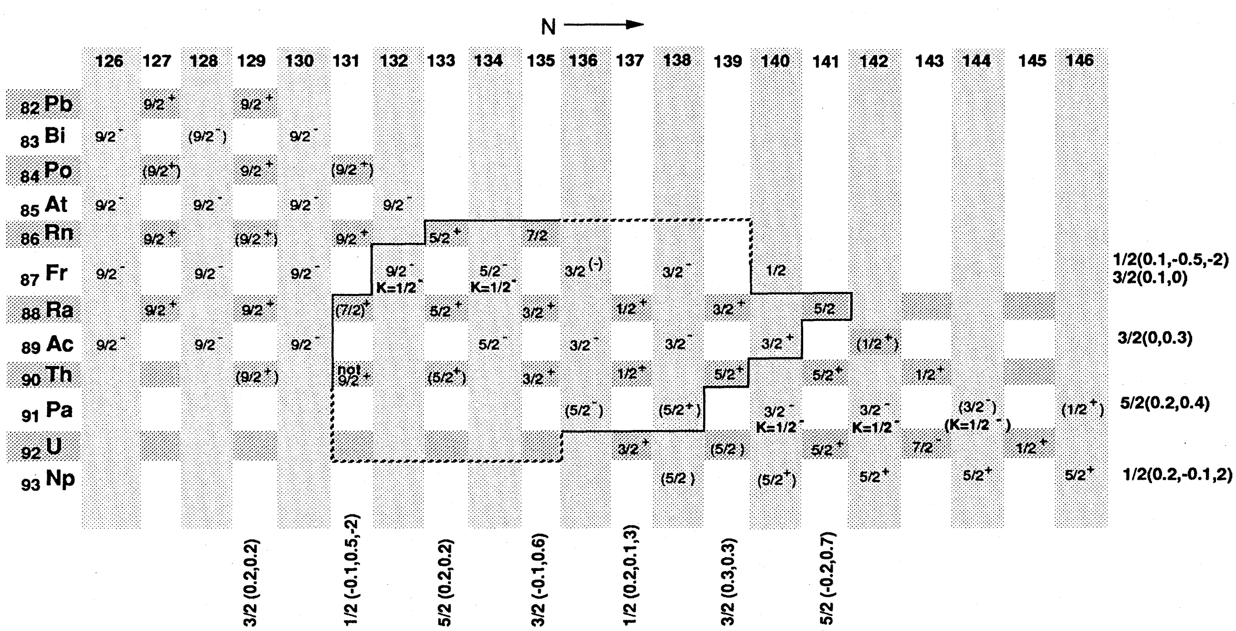

FIG. 32. Ground-state spins and parities of the odd-A nuclei beyond ^{208}Pb. The appropriate quadrupole-octupole deformed neutron and proton orbitals (see Figs. 10 and 11) are listed at the bottom and at the right of the figure, respectively. The region of the quadrupole-octupole deformation defined in this way is shown by solid or dotted lines. From Sheline (1988).

quadrupole deformation versus the energy of the parity-mixed orbitals to assign the appropriate orbital to a particular ground state. Unfortunately, such a diagram is unavailable. We therefore use the two-dimensional diagram (Figs. 10 and 11), in which the ϵ_3 value of 0.08 represents a mean for this region, and qualitatively estimate the effects of higher and lower octupole deformation using Fig. 12. Octupole deformation has been shown (Sheline, Chen, and Leander, 1988) to reach a value of 0.15 in ^{223}Ra. This is $\sim 50\%$ higher than the maximum values observed for even-even nuclei, which is not surprising since the odd particle is known to polarize the core in the direction of greater octupole deformation. Since the value $\epsilon_3 = 0.15$ is the highest value observed and ^{221}Ra is expected (Leander and Sheline, 1984) to have an equivalent ϵ_3 value, we assume that the octupole deformation falls off symmetrically and monotonically to both higher and lower neutron and proton numbers reaching the value 0.10 (Leander and Chen, 1987) in ^{227}Ac and 0.083 in ^{229}Th.

For quadrupole deformation, we use the functional dependence proposed by Grodzins (1962) ($\epsilon_2 = KA^{-7/3}/E_2^+$) and normalize it to the ϵ_2 values of 0.129 (Sheline, Chen, and Leander, 1988) and 0.17 (Leander and Sheline, 1984) for ^{223}Ra and ^{229}Th, respectively. This results in a fairly narrow band of ϵ_2 values in going from 0.081 to ~ 0.176 at neutron numbers 131 and 141, respectively. These values for ϵ_2 are somewhat lower than those normally encountered for these nuclei. They reflect the additional presence of fairly large ϵ_3 values, which result in lower ϵ_2 values.

Using these values of ϵ_3 and ϵ_2 with Figs. 10 and 11, we predict the occupation of the octupole modified proton and neutron orbitals listed to the right and at the bottom, respectively, of Fig. 32. We then compare the predicted orbitals and the observed ground-state spins and, upon agreement, are able to outline the region of quadrupole-octupole deformation shown by the heavy solid and dashed line in Fig. 32. In view of the changing values of ϵ_2 and ϵ_3 and the corresponding ambiguities in the comparisons, each proton and neutron number is discussed separately.

Proton no. 87 (Fr): Figure 10 predicts approximately degenerate $1/2(-0.1;-0.5;-2)$ and $3/2(0.1;0)$ orbitals with a preference for the 1/2 orbital at the lower value of ϵ_2. This is exactly what is found with $1/2^-$, $1/2^-$, $3/2^-$, and $3/2^-$ ground-state bands observed for the Fr isotopes with neutron numbers 132, 134, 136, and 138, respectively. The $9/2^-$ ground state of ^{219}Fr is the anomalous bandhead of the $K=1/2^-$ band $(-0.1;-0.5;-2)$ with a decoupling parameter of ~ 7 (Liang, Sheline, and Paris, 1989). It is interesting to note that this band also represents the ground state in ^{221}Fr. However, now the $9/2^-$ state has moved up to 38.5 keV and the ground state has spin parity $5/2^-$. At the higher values of ϵ_2 (0.16–0.20), there is again a preference for the 1/2 orbital (0.4;0.9;1) as observed for $^{227}_{87}$Fr$_{140}$. However, in contrast with the lower neutron orbitals, this ground-state spin can be explained using the normal Nilsson orbital 1/2[660]. Furthermore, Coc *et al.* (1985, 1987) have observed a reversal in odd-even staggering of the isotope shift at ^{227}Fr, which implies the cessation of most of the octupole deformation.

Proton no. 89 (Ac): Figure 10 suggests that the $3/2(0;-0.3)$ orbital will predominate. This is indeed observed for Ac nuclei with neutron numbers 136, 138, and 140. The nucleus $^{223}_{89}$Ac$_{134}$ with spin $5/2^-$ corresponds with the orbital $5/2(0;-0.2)$ at low ϵ_2 deformation.

Proton no. 91 (Pa): The orbital $5/2(0.2;0.4)$ is expected to dominate most of the ϵ_2 region, as experimentally observed. A clear transition to negligible octupole deformation occurs at $^{231}_{91}$Pa$_{140}$ and at higher neutron numbers with the observation of the $1/2^-[530]$ normal Nilsson orbital.

Neutron no. 131: The spectra of the isotones $^{219}_{88}$Ra$_{131}$ and $^{221}_{90}$Th$_{131}$ represent a challenging experimental dilemma. Cottle *et al.* (1986), using in-beam spectroscopy on ^{219}Ra, have suggested extensive "band" structure built on a tentative $9/2^+$ bandhead. Dahlinger *et al.* (1985, 1988) have also observed an extensive ground-state band structure in ^{221}Th, but have not assigned a ground-state spin. However, the alpha decay of ^{219}Ra and ^{221}Th into the $9/2^+$ ground states of ^{215}Rn and ^{217}Ra proceed with HF's of 110 and 49, respectively, clearly implying that the ground states of ^{219}Ra and ^{221}Th are not $9/2^+$ (see Fig. 32). In addition, the levels in ^{219}Ra populated in the alpha decay of ^{223}Th seem totally disconnected with the levels observed in the in-beam spectroscopy (El-Lawindy *et al.*, 1987). Very recent α-γ angular correlations have determined the ground-state spin of ^{219}Ra to be $7/2^+$ or $11/2^+$ with a preference for $7/2^+$ (Hackett *et al.*, 1989). Leander and Chen (1988) and Sheline and Sood (1990b) have suggested a ground-state spin of $7/2^+$ based on theoretical arguments. Perhaps the most reasonable explanation (totally unproven) is that we are observing the coexistence of weak coupling involving vibrational levels with alternating positive and negative parity (as observed in the in-beam spectroscopy) built on the $7/2^+$, $3/2^+$, $11/2^+$ lowest-lying states of an anomalous $K=1/2^+$ band expected from a quadrupole-octupole deformed system. Since, however, there is evidence for octupole deformation in the alternating positive and negative parities, and we do not have the spherical shell-model ground-state spin $9/2^+$, it seems reasonable to include these nuclei in the region of quadrupole-octupole deformation.

Neutron no. 133: The spins of all three isotones fit the predictions of the orbital $5/2(0.2;0.2)$.

Neutron no. 135: The spins of ^{223}Ra and ^{225}Th are explained with the parity-mixed orbital $3/2(-0.1;0.6)$. The 7/2 spin observed for ^{221}Rn probably results from the anomalous 7/2 bandhead arising from the decoupling of the $1/2(-0.1;0.5;-2)$ orbital. The small negative quadrupole moment supports this and may also suggest mixing with the $7/2(0.2;0.1)$ orbital.

Neutron no. 137: The spins of both ^{225}Ra and ^{227}Th correspond to the orbital $1/2(0.2;-0.1;3)$. However, the experimentally observed ground-state positive parity of the 137th neutron suggests that $\langle\hat{\pi}\rangle$ is greater than 0 and that there is mixing with the $1/2(-0.1;0.6;1)$ orbital at higher ϵ_3 values. A recent analysis of the experimental data on ^{225}Ra (Sheline, Jain, *et al.*, 1989) suggests a coexistence of reflection asymmetry and reflection symmetry in this nucleus. The normal Nilsson orbital $3/2^+[631]$ governs the ground-state spin of ^{229}U.

Neutron no. 139: The $3/2^+$ spin of ^{227}Ra can be understood by assuming that the last odd neutron occupies the $3/2(0.3;0.3)$ orbital (Fig. 11). The $5/2^+$ ground state of ^{229}Th corresponds more nearly to the $5/2^+[633]$ Nilsson orbital. However, less than 0.1 keV above the ^{229}Th ground state, a $3/2^+$ state is observed that is formed from the parity-mixed orbital $3/2(0.3;0.3)$, which is the ground state for ^{227}Ra. Thus we have the coexistence of the normal Nilsson orbital and the parity-mixed orbital less than 0.1 keV apart in ^{229}Th. Indeed, the $5/2^+$ ground state has a normal octupole vibrational $5/2^-$ state at 512 keV, while the $3/2^+$ state of ~ 0.1 keV has a parity doublet $3/2^-$ state at 164 keV. This coexistence of normal and mixed-parity states in ^{227}Ra and ^{229}Th (and also in ^{225}Ra) has been explained by the ability of the odd particle in different orbitals to polarize the soft nuclear core towards smaller or larger octupole deformations. This clearly observed coexistence is expected as the ϵ_3 deformation decreases and we approach normal quadrupole deformation.

Neutron no. 141: The $5/2$ spin of ^{229}Ra might be explained by using the parity-mixed orbital $5/2(-0.2;0.7)$ or by using the $5/2^+[633]$ Nilsson orbital, which is appropriate for ground-state spins of ^{231}Th and ^{233}U. However, in the case of ^{229}Ra, we have the radius change measurements of S. A. Ahmad *et al.* (1983, 1988). The anomalous even-odd shift due to octupole deformation has almost disappeared in the case of ^{229}Ra. This seems to suggest that, since the normal even-odd shift has not returned, we probably have approximately one-half of the octupole deformation which results in the vanishing even-odd shift. Thus the ^{229}Ra nucleus is tentatively included in the region of octupole deformation, anticipating a coexistence of simple prolate shapes and spectra.

We have thus compared the experimental spins of odd-A nuclei with predictions of the quadrupole-octupole single-particle model and are able to define the region of quadrupole-octupole deformation. In the transition regions, as octupole deformation tends toward zero, the assignment of octupole shape is more ambiguous. There is weak experimental evidence in the transition region around $N=131$ of the coexistence of spherical-octupole and prolate-octupole spectra and shapes. Further, for $N=137-139$, and particularly ^{225}Ra, ^{227}Ra, and ^{229}Th, there is strong experimental evidence for the coexistence of static-prolate–dynamic-octupole and static-prolate–static-octupole spectra and shapes.

2. Energy systematics of intrinsic states of octupole nuclei

In Fig. 33, we show the empirical energy systematics of the odd-Z and odd-N nuclei which lie in the octupole de-

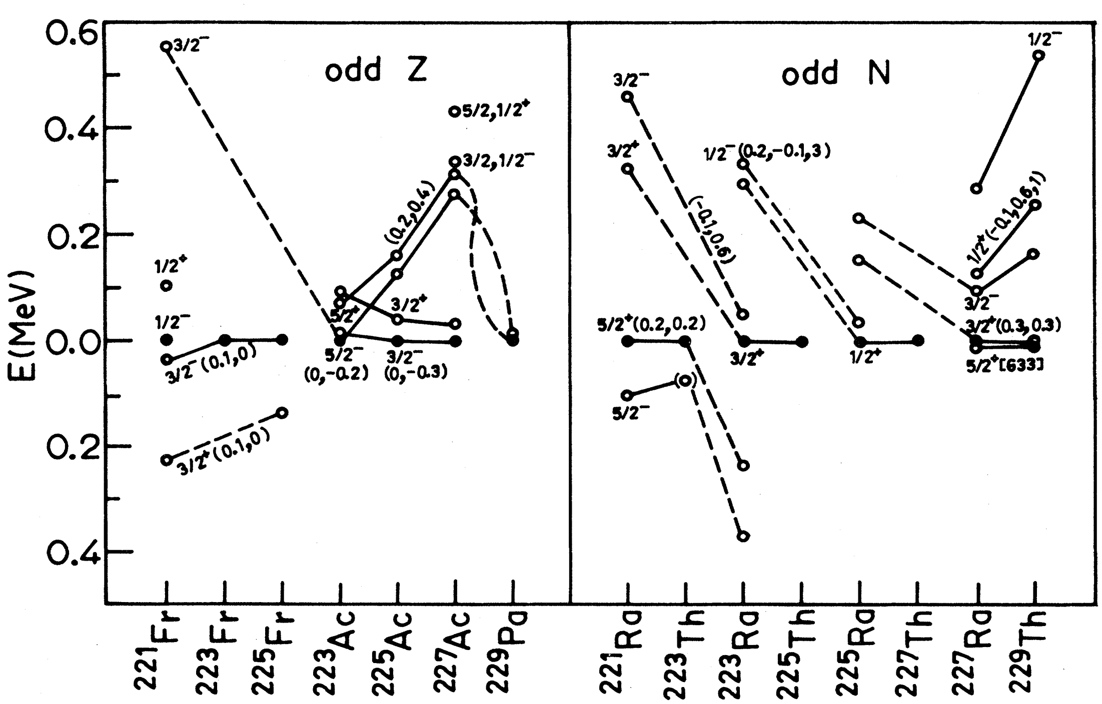

FIG. 33. Systematics of the odd-proton and the odd-neutron orbitals in the quadrupole-octupole deformed region of the actinides. The single-particle states are labeled by the values $(\langle\hat{s}_z\rangle,\ \langle\hat{\pi}\rangle,\ a_p\delta_{K=1/2})$ as defined in Sec. III.A.3.

formed region. The states have been classified into particle/hole states purely on the basis of the theoretical single-particle diagrams (Figs. 10 and 11) obtained for a folded Yukawa reflection-asymmetric potential.

The data presented in Fig. 33 are too limited. However, it is important to note that the parity doublet splitting is reasonably constant for given configurations from nucleus to nucleus. The configuration systematics is explained readily in terms of Figs. 10 and 11 if we take the proper variation in the octupole and quadrupole deformation into account. The increase in quadrupole deformation with increasing mass number causes the change in ground-state configuration between ^{221}Fr and ^{223}Fr and between ^{223}Ac and ^{227}Ac. In the odd-N nuclei the only change in the ground-state configuration for isotones is between ^{227}Ra and ^{229}Th, and there the change is less than 1 keV. Excited configurations also behave in a reasonably systematic way.

B. Other nuclei

A significant amount of new data on the other actinides has been gathered since the last review of Chasman *et al.* (1977). The experimental data on the 1qp intrinsic excitation energies of odd-proton and odd-neutron nuclei for $A \geq 231$ are presented in Figs. 34 and 35 (below). These figures have been plotted following the guidelines used for Figs. 15 and 16 in the rare earths.

1. One-quasiproton states

Figure 34 exhibits the energy systematics of the odd-proton states. Although the density of states is much greater in the actinides than in the rare earths, the data available are relatively more sparse. Still the systematics presented in Fig. 34 represents a much more complete picture than was available earlier (Ellis and Schmorak, 1972; Erskine *et al.*, 1975; Hoff, 1975).

Figure 34 indicates clearly that the ground-state assignments are changing systematically in going from one set of isotopes to the next; the particle state becomes the ground state and the ground state becomes the hole state, in an orderly fashion. There are, however, changes in the observed ground state near the end of each isotopic sequence in which one of the hole states becomes the ground state and the ground state becomes a hole state. The $Z=93$ systematics is different in this regard. These crossings can be explained in terms of the Nilsson diagram shown in Fig. 7. The crossing at ^{237}Pa between $1/2^-[530]$ and $1/2^+[400]$ clearly represents the effect of increasing ϵ_2 deformation and is present in the theoretical Nilsson scheme near $\epsilon_2 \approx 0.25$. The crossing between $5/2^+[642]$ and $5/2^-[523]$ seen in ^{245}Am, however, seems to be the result of a slight decrease in ϵ_2 deformation. Theoretical calculations indeed predict a decrease in deformation for ^{246}Pu, ^{248}Cm, etc., which lie at the end of their respective isotopic chains (see Fig. 9). Such a reversal in the deformation can explain the crossing of

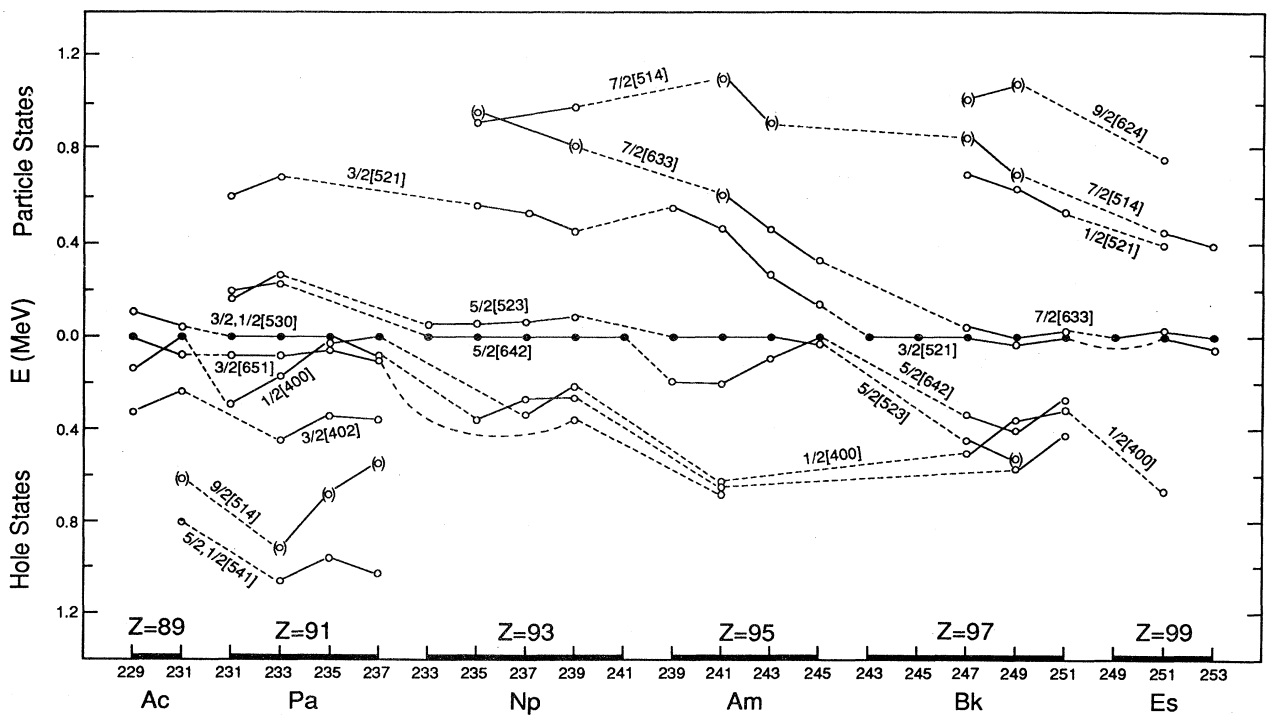

FIG. 34. Experimental single-proton energy systematics for the actinides: ●, ground states. Predominantly particle and hole states are plotted above and below the ground states, respectively.

$5/2^+[642]$ and $5/2^-[523]$ seen in the calculated level scheme at $\epsilon_2 \approx 0.22$.

The changes in the ground-state configurations of ^{249}Bk, ^{251}Bk, and ^{251}Es, ^{253}Es isotopes correspond to a shift of the ground states between the close-lying $3/2^-[521]$ and $7/2^+[633]$ orbitals. In the calculated single-particle-level scheme, these two orbitals lie very close to each other and are nearly parallel for a considerable range of deformation ($\epsilon_2 \approx 0.18$ to 0.3). We point out that the Nilsson scheme shown in Fig. 7 is plotted only for the negative value of the ϵ_4 deformation. Most of the nuclides in the actinide region have a negative ϵ_4 value. However, the ϵ_4 deformation approaches zero near $A = 246$ and becomes positive for $A > 246$. By assuming a change in the sign of ϵ_4, we can reproduce the observed changes in the empirical systematics of the Bk and Es isotopes.

We note that the data on the ground-state configurations of ^{255}Md and ^{257}Md, which are both assigned as $7/2^-[514]$, are not included in the plots and the table.

a. The proton gaps

Energy-level gaps have been shown to be important because of their stabilizing effects. Three gaps are apparent in the calculated Nilsson scheme at $Z = 92$, 96, and 100 (see Fig. 7). Of these, the $Z = 100$ is the most prominent. All three gaps are present in the empirical systematics. The $Z = 92$ gap is seen for the $Z = 91$, 93, and 95 isotopic chains. The $Z = 96$ gap is present in nearly all the isotopic chains; it exists as a gap in the particle states up to $Z = 95$ and then as a gap in the hole states for $Z = 97$ and 99. The $Z = 100$ gap is seen for $Z > 95$ nuclei.

b. Comparison of the experimental and theoretical systematics

We have explicitly compared the predictions of the Nilsson model with those of the experimental data for many isotopic chains, as was also done in the rare earths, and have found that the agreement is not as good as that found for the rare-earth region. The Woods-Saxon potential definitely provides a better description of the 1qp states for actinides; however, an improved set of parameters of the Nilsson model, obtained by fitting the spherical Nilsson levels to the corresponding Woods-Saxon levels, may be used to provide a more satisfactory description (Bengtsson *et al.*, 1989). Similar remarks apply to the odd-neutron systematics of the actinides.

c. Comparison of odd-proton actinides and odd-neutron rare-earth systematics

The odd protons in the actinides and the odd neutrons in the rare earths fill the same major shells and therefore the same Nilsson orbitals. For this reason it is interesting to compare the systematics of Fig. 34 for the actinides and the systematics of Fig. 16(a) for the rare earths. In the Nilsson model for the actinides the $f_{7/2}$ orbital is filled after the $h_{9/2}$ and $i_{13/2}$ orbitals, whereas it is filled before the $h_{9/2}$ and $i_{13/2}$ orbitals in the rare earths. The experimental level scheme, as also predicted by the Woods-Saxon potential, puts the $f_{7/2}$ orbital between the $h_{9/2}$ and $i_{13/2}$ orbitals for the actinides. The Nilsson model correctly predicts the location of the $f_{7/2}$ orbital in the rare earths. With this difference in mind, the odd-proton $Z = 89$ to 99 systematics of the actinides is remarkably similar to the $N = 89$ to 99 systematics of the rare earths.

d. Superheavy elements and the Z = 114 gap

It is interesting to note that the next shell closure for the actinides is predicted at $Z = 114$ (Meldner, 1967, 1969), whereas it occurs at $N = 126$ in the rare earths. Thus $Z = 97$ and 99 already correspond to the middle of the shell for the actinides. There is a slight indication in the $Z = 97$ isotopic chain that the $1/2^-[530]$, $1/2^+[400]$, and $5/2^+[642]$ orbitals are beginning to reverse their trend toward deeper hole states, which was also observed more clearly for the $Z = 73$ and 75 isotopic chains in the rare-earth region. Although more data are needed to ascertain this trend, it might ultimately prove very useful in confirming the collapse of the Nilsson orbitals toward the next magic number at $Z = 114$. This, in turn, could prove important in finding superheavy nuclei.

The $1/2^-[521]$ state (arising from the $f_{5/2}$ orbital above the 114 gap) is expected to appear as a particle excitation, and the $1/2^-[530]$ state (arising from the $f_{7/2}$ orbital below the gap) is expected to appear as a deep-hole excitation for $Z = 97$ to 99 nuclei. The relative position of these two $1/2^-$ Nilsson orbitals can therefore indicate the $f_{7/2}$-$f_{5/2}$ splitting, which is crucial in predicting the gap at $Z = 114$ for spherical superheavy nuclei. Both these states have been seen in Bk isotopes ($Z = 97$). The $1/2^-[521]$ state appears at an excitation (~ 700 keV) that is below the $7/2^-[514]$ orbital, contrary to Nilsson-model estimates. The $1/2^-[530]$ hole state appears at ~ 600 keV; it is, however, placed in correct order after the $5/2^+[642]$ and the $5/2^-[523]$ states. Calculations performed by Gareev *et al.* (1971) suggest an admixture of γ vibration based on the $3/2^-[521]$ state in both of these $1/2^-$ states. It is also suggested that these $1/2^-$ states admix. The empirical decoupling parameter values of the $1/2^-[521]$ band for ^{247}Bk, ^{249}Bk, and ^{251}Bk are $+0.89$, $+0.02$, and $+0.11$, as compared to the Nilsson-model estimate of $\approx +1.4$. It is, therefore, quite likely that the vibrational admixture is present. However, the decoupling parameter of the $1/2^-[530]$ band is only slightly reduced in ^{249}Bk, ^{251}Bk, and ^{251}Es. The vibrational admixture in the $1/2^-[530]$ state should therefore be small, and calculations support this conclusion. If these vibrational admixtures can adequately be taken into account, so that the positions of the pure $1/2^-$

Nilsson orbitals are calculated, the $f_{7/2}$-$f_{5/2}$ splitting can be determined.

A comparison of the level structure of ^{249}Bk with the Nilsson model and the Woods-Saxon (plus phonon) model has been made by Hoff (1975). A good agreement between the empirical and the Woods-Saxon–plus–phonon calculations was obtained. It therefore appears that the present models can correctly explain the splitting of the $1/2^-[521]$, $f_{5/2}$ and $1/2^-[530]$, $f_{7/2}$ states. These observations support the existence of a gap at $Z=114$.

2. One-quasineutron states

Figure 35 summarizes the one-quasineutron energy systematics of the actinides. Similar systematics were presented earlier by Börner (1985); our plot, however, contains a substantially larger body of data.

The ground-state configuration assignments change in a systematic manner as we move from one set of isotones to the next. The Nilsson model successfully predicts these configurations, if proper variation in the deformation is taken into account. The Nilsson-model plots presented by Bengtsson *et al.* (1989) are particularly useful for such a comparison, as they have been plotted for typical deformation values for the $N=142$ to 156 isotonic chains. The only discrepancy occurs for $N=153$, where the Nilsson model predicts $7/2^+[613]$ as the ground state, whereas the empirical ground-state configuration is $1/2^+[620]$. However, $7/2^+[613]$ does become the ground state in ^{253}Cf.

a. The neutron gaps

Three gaps are observed in the empirical systematics: $N=142$, 150, and 152. The calculated Nilsson scheme, particularly that presented by Bengtsson *et al.* (1989), explains all three gaps reasonably well.

b. Effect of the hexadecapole deformation

As pointed out in the discussion of rare earths, the increasing ϵ_4 deformation has a dramatic effect on the intruder states, i.e., states coming down from the next higher oscillator shell. In the actinides, the ϵ_4 is negative near $A=234$, changes sign near $A=246$, and becomes positive. This change in ϵ_4 also leads to a closer grouping of the intruder states, particularly the low-K states. This

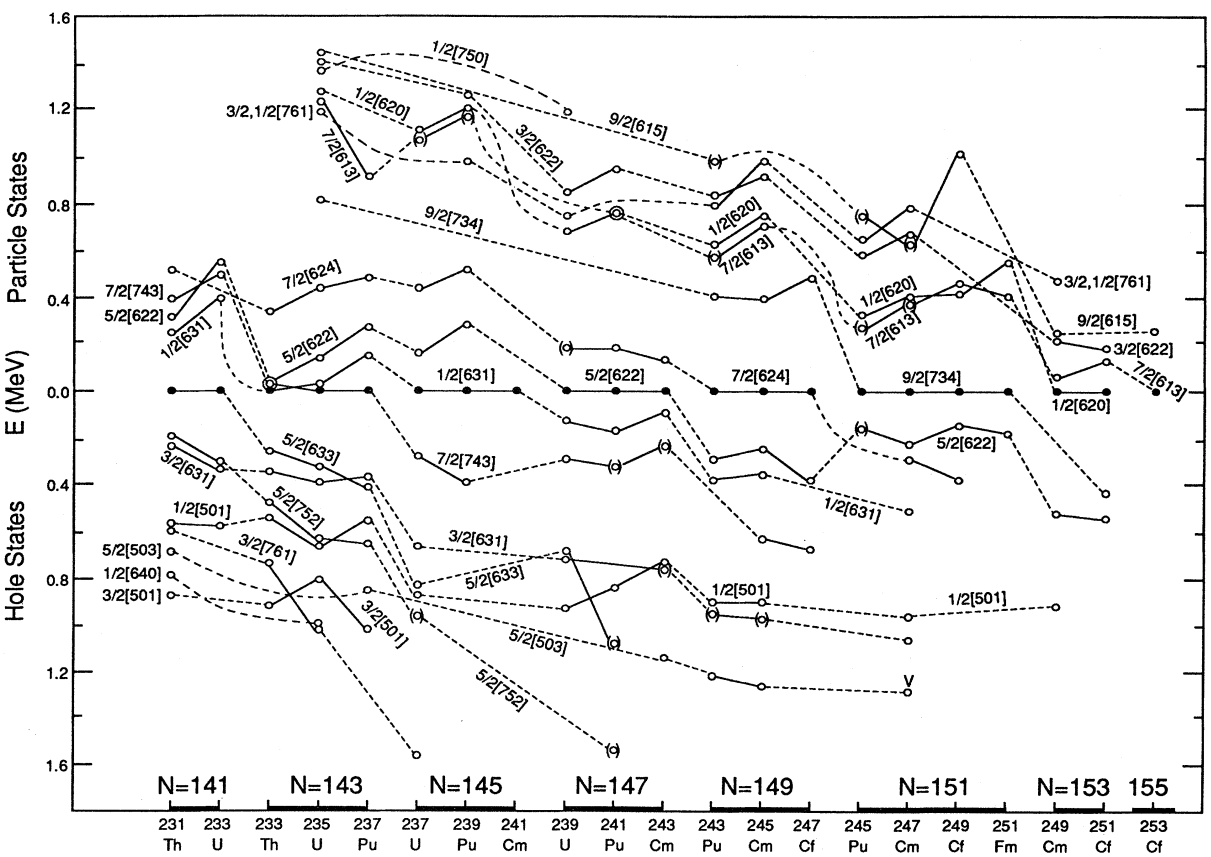

FIG. 35. Experimental single-neutron energy systematics for the actinides: ●, ground states. Predominantly particle and hole states are plotted above and below the ground states, respectively.

behavior is clearly observed in Fig. 7 for the $i_{13/2}$ proton states and is also present to some extent in the $j_{15/2}$ neutron states (see Fig. 8).

c. Anomalous decoupling parameter values

The empirical decoupling parameters for $K=1/2$ bands in odd-Z and odd-N actinides are summarized in Tables XLIII and XLIV, respectively, where we also compare them with the Nilsson-model values.

The empirical decoupling parameters for the $1/2^-[530]$ bands, though slightly smaller than the Nilsson-model values, are, with the exception of ^{229}Ac and ^{235}Pa, in reasonable agreement with theory, considering the fact that a small γ-vibrational component may be admixed. The small value of $a=-0.75$ in ^{229}Ac is probably the effect of octupole deformation. However, the very small value $(a=-0.35)$ for ^{235}Pa remains unexplained.

The empirical decoupling parameters of $1/2^+[400]$ bands are only slightly larger than the Nilsson-model values. In ^{229}Ac and ^{231}Ac, however, the empirical values are nearly 3 times the Nilsson estimates. This severe deviation undoubtedly results from both of these nuclei being in the transitional octupole-quadrupole deformed region.

The decoupling parameter values for the $1/2^-[521]$ bands are all smaller than the Nilsson-model values because of the γ-vibrational admixture and some mixing with the $1/2^-[530]$ state.

The decoupling parameters of the odd-N actinides are satisfactorily explained by adopting an improved set of parameters due to Bengtsson and Frisk (1988). There are some anomalies that need to be explained, however. The decoupling parameter of the $1/2^-[761]$ band in ^{227}Ra has a value $a=+1.83$, whereas the theoretical value is $a=-1.6$. Similarly, the decoupling parameter of the $1/2^+[631]$ state in ^{231}Th has a positive sign, while the Nilsson-model values are negative. We ascribe these differences to static and dynamic octupole effects in ^{227}Ra and ^{231}Th, respectively.

The anomalous value of the $1/2^+[620]$ decoupling parameter in ^{241}Pu is negative as compared to a positive value predicted by the Nilsson model using the improved set of parameters. We explain this as the effect of mixing the $\{5/2^+[622]\otimes 2^+\}$ vibration into this state.

The experimental decoupling parameters of the $1/2^-[750]$ state in ^{239}U and the $1/2^+[640]$ state in ^{231}Th must be considered to be tentative because of incompleteness or uncertainty in the data.

3. Vibrational excitations in the actinides

Like the rare earths, the odd-A actinide nuclei exhibit $K=0^+(\beta-)$, $K=2^+(\gamma-)$, and $K=0^-$ (octupole) vibrational states based on various one-quasiparticle states. Data on the vibrational excitations have been obtained by using Coulomb excitation, (d,d') and (p,t) reactions, and, more recently, (n,γ) and (n,e^-) reactions. Theoretical calculations and the empirical data suggest a frequent mixing of the vibrational modes and the single-particle modes of excitation. This is more extensive in the actinides than in the rare earths because of the increased level density. It is therefore difficult to find a pure vibrational excitation; accordingly, what we shall discuss are states in which the vibrational character is pronounced.

Energy systematics of the predominantly vibrational excitations were discussed earlier by von Egidy, Almeida, *et al.* (1979); Hoff, Lougheed, *et al.* (1982); and Börner (1985). There has, however, been a significant growth in the data since these studies. Therefore a compilation of the data on $\beta-$, $\gamma-$, and $K=0^-$ octupole vibrational states is presented in Table XLV. Most of the available data belong to odd-N actinides, and there are only three odd-Z actinides where any vibrational excitation has been identified.

The moment-of-inertia parameters of the three types of vibrations in these tables are either nearly the same or slightly smaller than those of the base states. The slightly smaller values were explained by von Egidy, Almeida, *et al.* (1979) in terms of decreased pairing in a vibrational state where several quasiparticle states are partially blocked.

The behavior of the decoupling parameters of the $1/2^+[631]$ base state was also discussed by von Egidy, Almeida, *et al.* (1979). We note that the decoupling parameter is positive for ^{231}Th and becomes increasingly negative in going to ^{239}U. This trend is explained as the effect of increasing quadrupole deformation, while the positive value in ^{231}Th may be explained as an octupole effect. However, the observed trend in the β bands based on the $1/2^+[631]$ state is opposite in going from ^{233}Th to ^{237}U. It is interesting to note that the $K=0^-$ bands

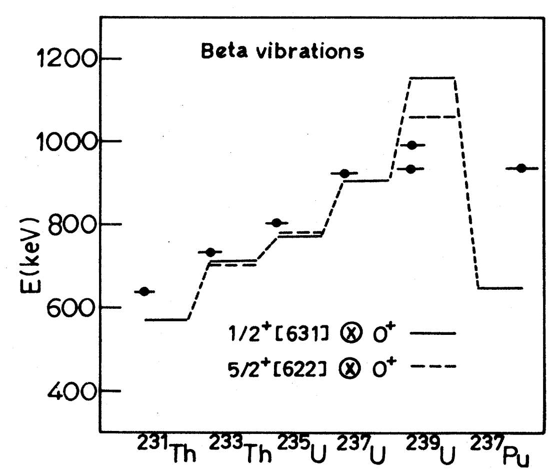

FIG. 36. Energy systematics of the $K=0^+$, β vibrations for odd-N actinides. The difference in the vibrational level energy and the base-state energy is plotted. Also shown for comparison are the β-vibrational energies of the neighboring even-even nuclei (dots).

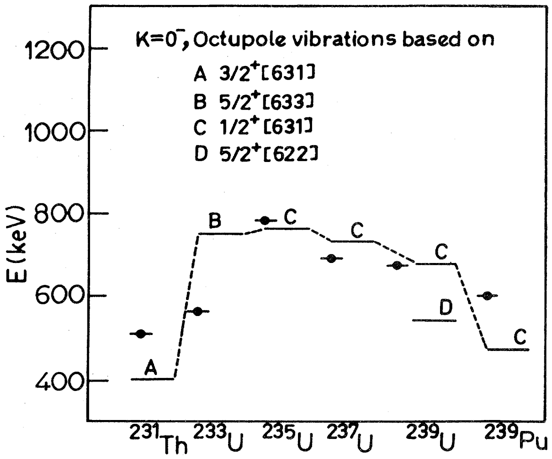

FIG. 37. Systematics of the $K=0^-$ octupole vibrations for odd-N actinides. For comparison, the octupole vibration energies of neighboring even-even nuclei are also plotted (dots).

display a parallel behavior. The sudden change in the decoupling parameter of the $K=0^-$ band in ^{237}U in comparison with those of ^{235}U and ^{239}U is probably the result of an admixture of the $1/2^-[501]$ single-particle state, which has a positive decoupling parameter.

The decoupling parameters of the $K=1/2^+$ γ vibration based on the $5/2^+[633]$ and $5/2^+[622]$ base states should be zero; however, the observed fairly large value is probably due to the admixture of the $1/2^+[620]$ configuration. This admixture was estimated by von Egidy, Almeida, *et al.* (1979) by using the empirical cross-section data on the (d,p) reaction and its comparison with the theoretical estimates. The $1/2^+[620]$ state admixture in ^{233}Th, ^{235}U, ^{237}U, and ^{239}U was estimated to be about 24%, 30%, 28%, and 53%, respectively, which is in reasonable agreement with the results of Soloviev's calculations (Gareev *et al.*, 1971; Komov *et al.*, 1972).

The β-vibrational energies based on the $1/2^+[631]$ and the $5/2^+[622]$ neutron states, for which the most complete data are available, are plotted in Fig. 36. Also shown are the β-vibrational states of the $(A-1)$ even-even nuclei for comparison. The odd-A β-vibrational states follow approximately the trend of the even-even core vibrations.

We show in Fig. 37 the systematics of the octupole vibrational states. We note that the octupole vibrations also follow the even-even systematics reasonably well.

Finally we have also plotted the energy systematics of the gamma-vibrational states in Fig. 38. It is probably significant, but unexplained, that the gamma-vibrational states of odd-A actinides do not follow the trend exhibited by the vibrational states of the even-even actinides. This is in clear contrast to the systematics of gamma-vibrational states in odd-A rare earths.

IX. CONCLUSIONS

In this review we have compiled the detailed spectroscopic information on the intrinsic states of deformed odd-A nuclei with $151 \leq A \leq 193$ and $A \geq 221$. The global approach employed, in contrast to the nucleus-to-nucleus approach previously used, is particularly useful for studying a variety of systematics, some of which have been discussed here. We believe that the tables should be of much use in a wide variety of additional systematic studies.

We have emphasized the transition regions in this study, in part because they were not covered in previous reviews, and in part because many of the newest initiatives have occurred in these regions. These include the striking collapse in level energies and the coalescence of single-particle reaction cross sections, both at the beginning and at the end of the deformed regions, implied by the higher symmetry restoration with the approach to

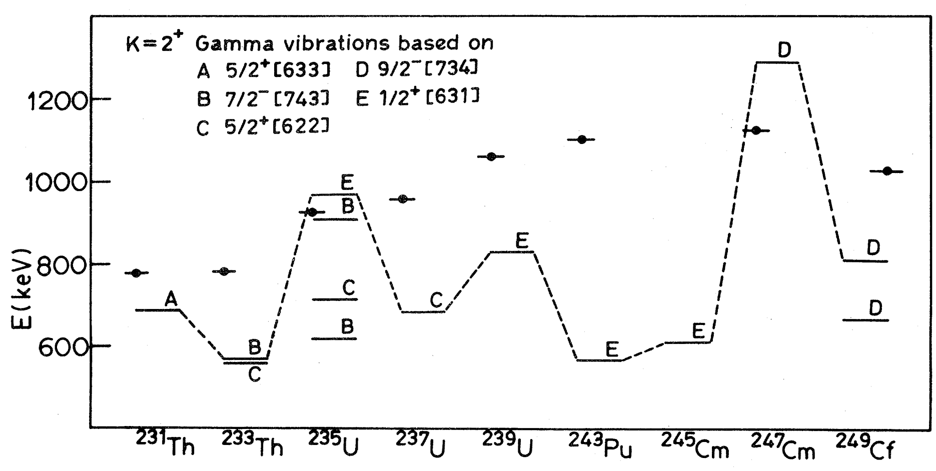

FIG. 38. Systematics of the $K=2^+$ gamma vibrations for odd-N actinides. For comparison, the gamma-vibrational energies of neighboring even-even nuclei are also plotted (dots).

the more degenerate shell-model orbitals. The new initiatives also include the observation of strong octupole correlations at the beginning of both the rare-earth and the actinide regions; the correlations can be interpreted in terms of octupole-quadrupole deformation. While the framework for understanding the intrinsic one-quasiparticle states is the Nilsson model (with the octupole or hexadecapole deformation parameters where needed), the collective excitations and multiparticle states are understood in terms of the more general deformed potential models.

It is clear that experimental information on the intrinsic states of odd-A deformed nuclei will continue to accumulate. The data on the vital transition regions will define and extend the realm of applicability. It is especially clear that the experimental data on superdeformation and on octupole deformation will grow rapidly in the coming years. It is to be hoped that the theoretical developments will keep pace with experiment. In particular, it would be very exciting to see the Hartree-Fock-Bogoliubov treatment of odd-A nuclei further refined and used extensively for both quadrupole and octupole-quadrupole deformations. In a similar way the IBFA group theory approach should be very valuable because of its ability to treat the transition regions in such a natural way. Finally, it would be interesting to see how the treatment of $\epsilon_2, \epsilon_3, \epsilon_4, \ldots, \epsilon_7$ as independent variables in a self-consistent way over the entire range of the rare earths and actinides would modify the Nilsson model and the intrinsic states which it predicts.

Note added in proof. The following are updated mass chain evaluations, related to our regions of interest, published by Nuclear Data Sheets evaluators after our literature cutoff dates:

$A=161$:	Helmer, R. G., 1990, Nucl. Data Sheets **59**, 1.
$A=167$:	Shirley, V. S., 1989, Nucl. Data Sheets **58**, 871.
$A=185$:	Browne, E., 1989, Nucl. Data Sheets **58**, 441.
$A=229$:	Akovali, Y. A., 1989, Nucl. Data Sheets **58**, 555.
$A=233$:	Akovali, Y. A., 1990, Nucl. Data Sheets **59**, 263.
$A=249$–265 (odd):	Schmorak, M. R., 1990, Nucl. Data Sheets **59**, 507.

ACKNOWLEDGMENTS

The authors are grateful to Yvonne Sheline for her continued assistance throughout these investigations. Thanks are also due to S. Pearlstein and his colleagues at the National Nuclear Data Center, Brookhaven National Laboratory, for providing access to up-to-date references. Financial support from the National Science Foundation under Grant No. PHY89-06613 at Florida State University, the Department of Atomic Energy (India) at the University of Roorkee, and the University Grants Commission (India) at the Banaras Hindu University is gratefully acknowledged. One of us (K.J.) acknowledges the award of a Research Associateship from the Council of Scientific and Industrial Research (India) for part of the period when this work was done.

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